Title

Potential benefits of cool walls on residential and commercial buildings across California and the United States: Conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants

Authors
Rosado, PJ
Levinson, R

Publication Date
2019-09-15

DOI
10.1016/j.enbuild.2019.02.028

Peer reviewed

This document is a pre-print of the following publication:

Rosado, P. J., & Levinson, R. (2019). Potential benefits of cool walls on residential and commercial buildings across California and the United States: Conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants. *Energy and Buildings*, 199, 588–607. https://doi.org/10.1016/j.enbuild.2019.02.028

Potential benefits of cool walls on residential and commercial buildings across California and the United States: conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants

Pablo J. Rosado[1] and Ronnen Levinson[2]

Heat Island Group, Energy Technologies Area, Lawrence Berkeley National Laboratory

[1] pablojrosado@berkeley.edu

[2] RML27@cornell.edu (corresponding author)

Abstract

Solar-reflective "cool" walls reduce absorption of sunlight by the building envelope, which may decrease cooling load in warm weather and increase heating load in cool weather. Changes to annual heating, ventilation, and air conditioning (HVAC) energy use depend on climate, wall construction, wall orientation, building geometry, HVAC efficiency, and operating schedule. Changes to annual energy cost and energy-related emissions further vary with local energy prices and emission factors. We used EnergyPlus to perform over 100,000 whole-building energy simulations, spanning 10 different building categories, three building vintages, 16 California climate zones, and 15 United States (U.S.) climate zones.

Cool walls yielded annual source energy, energy cost, and emission savings in all California climate zones and in warm U.S. (ASHRAE) climate zones. In California, annual whole-building HVAC energy cost savings were 4.0 – 27% in single-family homes, 0.5 – 3.8% in medium offices, and 0.0 – 8.5% in stand-alone retail stores. In warm U.S. climates—zones 1A (Miami, FL) through 4B (Albuquerque, NM)—annual HVAC energy cost savings were 1.8 – 8.3% in single-family homes, 0.3 – 4.6% in medium offices, and 0.5 – 11% in stand-alone retail stores. California and U.S. fractional source energy and emission savings were comparable to fractional energy cost savings. Per unit surface area modified, cool-wall savings often exceeded cool-roof savings because building codes typically prescribe much less wall insulation than roof insulation.

Keywords

Cool wall; cool roof; energy savings; energy cost savings; emission reduction; solar reflectance; albedo; residential building; commercial building

Nomenclature

Abbreviations

AFUE	Annual fuel utilization efficiency
BECP	Building Energy Codes Program
CACZ	California climate zone
CBECS	Commercial Building Energy Consumption Survey
CDD18C	Cooling degree days at 18°C
CEC	California Energy Commission
COP	Coefficient of performance
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DOE	United States Department of Energy
eGRID	Emissions & Generation Resource Integrated Database
ESM	Electronic Supplementary Material
GHG	Greenhouse gas
GWP	Global warming potential
HDD18C	Heating degree days at 18°C
HVAC	Heating, ventilation, and air conditioning
IECC	International Energy Conservation Code
JESS	jEPlus Simulation Server
LBNL	Lawrence Berkeley National Laboratory
LT	Local time
NO_x	Nitrogen oxide
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwestern National Laboratory
RECS	Residential Energy Consumption Survey
SAF	Solar availability factor
SEEAT	Source Energy and Emissions Analysis Tool
SO_2	Sulfur dioxide
U.S.	United States
USCZ	United States climate zone

Symbols

a	Pollutant index
A_{m}	Total surface area modified
c	Annual whole-building HVAC energy cost savings
d_{HVAC}	Annual-average whole-building HVAC peak power demand reduction
e_{c}	Annual whole-building cooling site electricity savings
E_{c}	Annual whole-building cooling site electricity use
e_{f}	Annual whole-building fan site electricity savings
E_{f}	Annual whole-building fan site electricity use
e_{h}	Annual whole-building heating site electricity penalty
E_{h}	Annual whole-building heating site electricity use
f_{e}	State-specific site electricity emission factor
f_{g}	Non-regional site gas emission factor
g_{h}	Annual whole-building heating site gas penalty
G_{h}	Annual whole-building heating site gas use
h_{HVAC}	Annual whole-building HVAC source energy savings
i	Hour index
j	Whole-building savings
j''	Intensity (value per unit surface area modified) of savings j
p	Annual whole-building reduction in emission of pollutant
s_{e}	Site-to-source conversion factor for electricity
s_{g}	Site-to-source conversion factor for gas
T	Number of peak-demand hours in a year
z_{e}	State-specific annual average price of electricity
z_{g}	State-specific annual average price of gas

1 Introduction

Solar-reflective “cool” walls reduce absorption of sunlight by the building envelope, which may decrease a building’s cooling load in warm weather and increase its heating load in cool weather. The change in a building’s annual heating, ventilation, and air conditioning (HVAC) energy use depends on climate, wall construction, wall geometry, and wall orientation, along with other details of the building, such as HVAC efficiency and operating schedule.

The solar radiation (energy per unit area) that strikes a surface decreases with beam incidence angle, or angle between solar beam and surface normal. At noon in summer, the sun is high, and a horizontal roof receives beam (direct) solar radiation at a small incidence angle. In winter, the sun is lower, the roof’s solar incidence angle is greater, and the days are shorter (Abood 2015); in some climates, winter skies may also be cloudier (Wilcox and Marion 2008). Thus, we expect a horizontal roof to receive more daily solar radiation in summer than in winter.

The decrease in cooling load and increase in heating load upon raising wall albedo are each proportional to the sunlight intercepted by the walls. Thus, we expect walls that receive more sunlight to contribute more to the changes in cooling and heating loads.

Consider a building in the northern hemisphere with walls that face north, east, south, and west. On a clear day, we expect east and west walls to receive similar daily solar radiation given the east-west symmetry of the solar path. Beam solar radiation strikes the east wall in the morning and the west wall in the afternoon. The summer sun rises in the northeast and sets in the northwest. The solar path in summer peaks close to zenith in the southern sky. In winter, the sun rises in the southeast and sets in the southwest; the solar path peaks in the southern sky at a small elevation angle (Abood 2015; Schroeder 2011). Therefore, the north wall receives beam solar radiation only during early morning and late afternoon of summer days. Under clear skies, the south wall will receive more beam sunlight in winter than in summer because the sun is lower, the wall’s minimum beam incidence angle is smaller, and the wall is exposed to more hours of direct illumination (Abood 2015).

Given the differences in exposure to daily solar radiation based on orientation, we expect the north wall to yield the smallest summer cooling energy savings and smallest winter heating energy penalties among all walls. In summer, we expect the east and west walls to yield greater cooling energy savings than the north and south walls. During winter, we expect the south wall to yield the greatest heating energy penalties and the north wall to yield the smallest heating energy penalties.

In the United States (U.S.), the first building energy efficiency codes were developed in mid-1970s (Hunn 2010). Before the adoption of the first energy codes, residential buildings were erected with little insulation in roofs and often had little to no insulation in walls (Huang et al. 1999). Since then, new codes have been released periodically, often raising insulation requirements. The efficiency of HVAC systems has also increased over time (Table 8-1 in CEC

2016b). The service life of an HVAC system depends on its maintenance but is typically 15 to 25 years (Comfort-Pro 2015). Therefore, we expect cooling savings and heating penalties to be greatest in old buildings that were erected prior to the first building codes and have HVAC systems near end of service life. New buildings comply with the most stringent insulation and HVAC efficiency requirements. Hence, we expect new buildings to yield the smallest cooling savings and heating penalties.

Past and current U.S. building energy codes prescribe more insulation in roofs than in walls (Table 8-1 in CEC 2016b; Huang et al. 1999; Blum 2007). Therefore, code-compliant walls provide less resistance to heat flow across the envelope than code-compliant roofs. If a building's four walls (considered together) and roof have the same total opaque surface area, receive equal solar energy, and undergo the same increase in albedo (solar reflectance), we expect the walls to yield greater cooling energy savings and heating energy penalties because walls are less insulated than roofs. Of course, cool-surface energy savings will also scale with solar radiation and modified surface area.

Envelope insulation, solar radiation, and surface area are considered in detail in the current study. However, for a simple example, consider how the ratio of roof area to net wall area (wall area excluding openings, such as windows and doors) can vary between buildings. A one-floor building with a large footprint, such as a single-story box store, will often have a high ratio of roof area to net wall area. This ratio decreases with building height since the wall area is proportional to the number of floors while the roof area remains the same. In multi-floor buildings, a cool roof affects the HVAC energy use of only the top floor while cool walls influence the HVAC energy use of every above-grade floor. Thus all else being equal, we expect cooling savings and heating penalties from cool walls to be greater than those from a cool roof when the building has a low ratio of roof area to net wall area.

Many researchers have simulated cool roof energy savings and penalties in the U.S. (Akbari et al. 1999; Akbari and Konopacki 2005; Levinson and Akbari 2010; Parker et al. 1998), China (Gao et al. 2014); India (Bhatia et al. 2011), Spain (Boixo et al. 2012), Australia (Gentle et al. 2011), and in major cities around the world (Synnefa et al. 2007). However, there are fewer comprehensive studies of cool *walls*.

Petrie et al. (2007) used the building energy simulation tool DOE 2.2 to estimate cool-wall energy savings and penalties for a small house in seven U.S. cities, while Moujaes and Brickman (2003) used the 1-D transient heat transfer model RESHEAT to estimate the cool-wall cooling load reduction for a house in Las Vegas, NV. Zinzi (2016a) found cooling energy savings of 10 – 20% when cool walls were applied to a three-story residential building simulated in the Italian cities of Palermo, Rome, and Milan. A second study by Zinzi (2016b) simulated cool-wall cooling energy savings for residential prototypes in three Mediterranean cities (Marseille, France; Athens, Greece; and Cairo, Egypt), reporting savings of 0.2 – 2.9 kWh/m² wall per 0.1 increase in wall albedo.

Revel et al. (2014) simulated cool-tile walls on a five-story building and on a large single-story industrial building in three European cities (Madrid, Rome, and Palermo), obtaining annual conditioning (cooling + heating) energy savings in each case. Finally, Paolini et al. (2017) performed a four-year natural exposure study on vertical concrete slates coated white (initial albedo 0.75) and beige (initial albedo 0.46) in Milan, Italy; after four years, the aged albedos were 0.55 and 0.38, respectively. They then simulated a 10-story residential building using these new and aged wall albedos. The 0.20 drop in white-wall albedo increased annual cooling energy use 5% – 11% and reduced annual heating energy use 2 – 4%. Energy-use changes depended on whether the building had been retrofitted to comply with current Italian energy regulations.

In this paper, we quantify the effect of cool walls on isolated buildings. The use of solar availability factors (SAFs) to scale cool-wall energy savings for shading and reflection by neighboring buildings is detailed in a companion article by Levinson (2019). For example, that study found that annual cool-wall savings in Fresno, CA should be scaled by an SAF of 0.90 – 0.96 when the canyon between opposing walls has an aspect ratio (height/width) of 0.2, and that the SAF falls to 0.06 – 0.24 as the aspect ratio rises to 10. SAFs for two-story single-family homes in Fresno typically range from 0.5 to 0.9 depending on the orientation of the central (modeled) wall and the distance to its opposing (neighboring) wall.

We created code-compliant building prototypes representing three vintages of 10 categories of buildings. Using EnergyPlus—a whole-building energy use simulation program—we modeled the cooling, heating, and fan energy uses of each prototype to evaluate annual site energy, site peak power demand, source energy, energy cost, and emission savings upon raising wall albedo or roof albedo. Prototype simulations parametrically varied wall albedo or roof albedo, combination of walls modified, and orientation of the building's long axis (east-west or north-south). Simulations spanned climate zones across California and the United States.

We present in this paper a subset of the California and U.S. savings and penalties to compare (a) cool wall savings to cool roof savings; (b) cool wall savings between locations; (c) cool wall savings from modifying different wall combinations; (d) savings from different vintages; and (e) the sum of savings from walls modified one at a time to savings from modifying the same set of walls simultaneously.

2 Methodology

2.1 Locations

The effects of cool walls in California were evaluated in the 16 building climate zones established by California Energy Commission (CEC) (CEC 2015). To represent these 16 California climate zones (CACZs), the building energy simulations were executed using weather data from 16 representative cities or towns (Table 1). Electronic Supplementary Material (ESM) Figure A-1 in ESM Appendix A.1 shows the region covered by each California climate zone.

We also evaluated cool-wall effects in 15 ASHRAE climates zones across the United States, which we refer to as United States climate zones (USCZs). Table 2 lists the cities used to represent the U.S. climate zones and the locations of their weather stations; ESM Figure A-2 shows the region of each U.S. climate zone. The U.S. climate zones are numbered from hottest (USCZ 1A) to coldest (USCZ 8). The letter in the U.S. climate zone name helps distinguish humid (A), dry (B), and marine (C) climates (Briggs et al. 2003a,b).

Table 1. Cities or towns in California used to represent its 16 building climate zones, and the locations of their weather stations.

City or town	California climate zone (CACZ)	Weather station location	
		Latitude and longitude	Elevation (m)
Arcata	1	40.98° N, 124.10° W	62
Santa Rosa	2	38.51° N, 122.81° W	45
Oakland	3	37.72° N, 122.22° W	3
San Jose	4	37.37° N, 121.93° W	16
Santa Maria	5	34.92° N, 120.47° W	77
Long Beach	6	33.83° N, 118.17° W	8
San Diego	7	32.73° N, 117.17° W	4
Fullerton	8	33.87° N, 117.98° W	29
Burbank	9	34.20° N, 118.35° W	226
Riverside	10	33.90° N, 117.25° W	462
Red Bluff	11	40.15° N, 122.25° W	106
Sacramento	12	38.50° N, 121.50° W	5
Fresno	13	36.78° N, 119.72° W	102
China Lake	14	35.68° N, 117.68° W	677
Imperial	15	32.83° N, 115.58° W	-17
Mount Shasta	16	41.33° N, 122.33° W	1078

Table 2. Cities in United States used to represent ASHRAE climate zones, and the locations of their weather stations.

City	State	United States climate zone (USCZ)	Weather station location	
			Coordinates	Elevation (m)
Miami	Florida	1A	25.85° N, 80.30° W	11
Houston	Texas	2A	24.70° N, 46.80° W	612
Phoenix	Arizona	2B	30.00° N, 95.37° W	29
Memphis	Tennessee	3A	33.45° N, 111.98° W	337
El Paso	Texas	3B	35.07° N, 89.98° W	81
San Francisco	California	3C	31.77° N, 106.50° W	1186
Baltimore	Maryland	4A	37.62° N, 122.40° W	2
Albuquerque	New Mexico	4B	39.17° N, 76.68° W	45
Salem [a]	Oregon	4C	35.04° N, 106.62° W	1619
Seattle [b]	Washington	4C	44.90° N, 123.00° W	60
Chicago [a]	Illinois	5A	47.47° N, 122.32° W	122
Peoria [b]	Illinois	5A	41.98° N, 87.92° W	201
Boise	Idaho	5B	40.67° N, 89.68° W	199
Burlington	Vermont	6A	43.62° N, 116.21° W	701
Helena	Montana	6B	49.18° N, 123.17° W	2
Duluth	Minnesota	7	44.47° N, 73.15° W	101
Fairbanks	Alaska	8	46.60° N, 111.97° W	1167

[a] For commercial prototypes only.

[b] For residential prototypes only.

2.2 Representative building vintages

The 2012 Commercial Building Energy Consumption Survey, or CBECS (EIA 2012) and 2009 Residential Energy Consumption Survey, or RECS (EIA 2009) were used to assess the age distribution of the country's current building stock by census division (for commercial buildings) or by state (for residential buildings). In most of the U.S. (including California), 40% to 60% of the buildings were erected before 1980. The decade of 1980 was typically the next period with significant building construction. In recent years, many states have also experienced rapid construction. ESM Appendix A.2 details our analysis of the age of U.S. buildings.

To represent California and U.S. building stock, this study analyses the effects of cool walls in three different building vintages: (a) *new* (for construction following current [2004 – 2016] building codes), (b) *older* (for buildings erected in the 1980s), and (c) *oldest* (for pre-1980 buildings). In many U.S. regions, the older and oldest vintage prototypes represent about 75% of the residential building stock and 70% of the commercial building stock (ESM Appendix A.2).

2.3 Building prototypes

2.3.1 Source of residential-building prototypes

The United States Department of Energy (hereafter, DOE) provides through its Building Energy Codes Program (BECP) a collection of prototypes for two residential building categories: single-family home and apartment building. These prototypes were generated to evaluate the energy and economic savings available by upgrading building energy efficiency standards to the latest version of the International Energy Conservation Code (IECC). BECP provides three sets of prototypes, each following a different IECC edition (year 2006, 2009, or 2012) (PNNL 2016a). BECP's collection of residential prototypes includes versions for 199 cities across United States, covering all 15 U.S. climate zones. BECP provides variants of each residential prototype with different building foundations (slab, crawl space, heated basement, or unheated basement) and heating systems (gas furnace, oil furnace, heat pump, or electric resistance).

To study cool walls in California, we selected BECP single-family home and apartment building prototypes with concrete slab foundation and gas furnace heating. These two prototypes were then modified following HVAC efficiency and building envelope insulation prescriptions in California's Title 24, Part 6—hereafter, simply "Title 24"—building energy efficiency standards. A version of each prototype was generated for each of California's 16 climate zones. In new construction prototypes, we set the HVAC efficiencies as well as the roof and wall insulation levels in accordance with 2016 Title 24 (CEC 2016b). Roof and wall insulation levels in older vintage prototypes were assigned following 1988 Title 24 (CEC 1988), while those in the oldest vintage were set using envelope properties typical of buildings constructed before 1978—the year of the first Title 24 standards. The HVAC efficiencies of the older and oldest California residential prototypes comply with 2005 Title 24 standards (CEC 2005). California prototype HVAC efficiencies and insulation levels are further detailed in Section 2.3.4 and Section **Error! Reference source not found.**, respectively.

To study cool walls throughout the U.S., we selected BECP prototypes defined in the 15 U.S. climate zones listed in Table 2. Each prototype has a concrete slab foundation. We simulated three heating systems (gas furnace, heat pump, and electric resistance) in each U.S. climate zone. Each of the 15 cities used to represent the 15 ASHRAE climate zones is in a different U.S. state. Since the rate of IECC adoption varies by state (BCAP 2017), the prototypes selected to represent new residential buildings in each of the 15 cities follow the IECC edition currently mandated in the state containing that city (ESM Table B-1 in ESM Appendix B).

Starting from these new construction prototypes, we generated the older and oldest vintage prototypes, setting roof and wall insulation levels following Huang et al. (1999) and HVAC efficiency following IECC 2006 (IECC 2006). HVAC efficiencies and insulation levels in the U.S. prototypes are further detailed in Section 2.3.4 and Section **Error! Reference source not found.**, respectively.

ESM Table B-2 describes geometry, envelope construction, and HVAC system for each vintage of the single-family home.

2.3.2 Source of commercial-building prototypes

DOE, in collaboration with three national laboratories[1], developed reference prototypes of 15 commercial building categories that represent realistic building characteristics and construction practices in the U.S. (Deru et al. 2011). DOE produced a suite of prototypes that follows pre-1980 construction practices, and another that follows ASHRAE Standard 90.1-1989. To represent new constructions, DOE has periodically released versions of their prototypes that follow more recent editions of ASHRAE 90.1 (i.e., 2004, 2007, 2010, and 2013) (PNNL 2016b).

The CEC adapted the prototypes of eight of the 15 DOE commercial building categories to meet 2008 Title 24. For our California study, we modified the CEC prototypes to represent oldest, older, and new vintages in California. The insulation levels in the oldest vintage follow pre-Title 24 construction practices. In the older vintage, insulation levels comply with 1988 Title 24 (CEC 1988). The HVAC efficiencies in the older and oldest vintage meet 2005 Title 24 (CEC 2005). In the new vintage, insulation levels and HVAC efficiencies comply with 2016 Title 24 (CEC 2016a).

For our U.S. study, we selected from DOE prototypes the eight commercial building categories used in the California study. The DOE prototypes that follow pre-1980 construction practices were used to represent the oldest vintage, while those that comply with ASHRAE 90.1-1989 were used to represent the older vintage. The HVAC efficiencies in the older and oldest vintage comply with ASHRAE 90.1-2001. We simulated new commercial buildings with the prototypes in each of the 15 cities that follow the ASHRAE 90.1 edition currently mandated in the state containing that city (ESM Table B-1).

The geometry, envelope construction, and HVAC system are described by vintage for the medium office building (hereafter, "medium office") and stand-alone retail store (hereafter, "stand-alone retail") in ESM Table B-3 and ESM Table B-4 respectively.

2.3.3 Building category geometry

ESM Figure B-1 illustrates the 10 building prototypes simulated in this study and ESM Table B-5 summarizes the geometry of each building category.

[1] The National Renewable Energy Laboratory (NREL), Pacific Northwestern National Laboratory (PNNL), and Lawrence Berkeley National Laboratory (LBNL).

2.3.4 HVAC efficiencies

An air conditioner or furnace has a service life of about 15 to 25 years, depending on how well it is maintained (Comfort-Pro 2015). Thus, we expect that HVAC systems in older and oldest vintage buildings have been replaced at least once and that current HVAC systems in these buildings can be anywhere from 0 to 25 years old. Since the age of the HVAC system in these vintages varies widely, we assume for purposes of this study that the HVAC system in an older or oldest vintage building is on average 10 years old. For such prototypes, we assigned HVAC efficiencies that comply with building codes in effect 10 to 15 years ago.

For the California study, the HVAC efficiencies in the older and oldest vintage prototypes were modified to match 2005 Title 24 standards (CEC 2005), while those in all new prototypes were set to follow 2016 Title 24 standards (CEC 2016c). ESM Table B-6 specifies the air conditioner cooling coefficient of performance (COP), and the gas furnace annual fuel utilization efficiency (AFUE) or electric heat pump heating COP, assigned to each vintage and building category in California.

For the U.S. study, we modified the HVAC efficiencies in the older and oldest vintage prototypes to comply with ASHRAE 90.1-2001 (ASHRAE 2001) in the commercial buildings and with IECC 2006 (IECC 2006) in the residential buildings. In new vintage prototypes, we set the HVAC efficiencies in accordance with the ASHRAE 90.1 edition currently mandated in the state containing the city simulated for each U.S. climate zone. ESM Table B-7 and ESM Table B-8 give the furnace AFUE, heat pump heating COP, and air conditioner cooling COP by vintage in the residential and commercial buildings, respectively.

2.3.5 Envelope construction

All residential prototypes in California and U.S. were simulated with wood-frame walls. Their roofs were simulated with a wood-frame attic (ESM Table B-10 and ESM Table B-11).

In California, the envelope construction of each building category did not vary by vintage. Most commercial buildings were simulated with metal-frame walls and a metal-frame roof. The large hotel had heavy mass walls (ESM Table B-10).

In the U.S., the large hotel and large office were simulated with heavy mass walls and a metal-frame roof in all vintages. Each medium office and strip mall retail building was modeled with metal-frame walls and a metal-frame roof. The envelope construction of the small office building, fast-food restaurant, stand-alone retail, and sit-down restaurant varied by vintage **(**ESM Table B-11**)**. For example, the oldest stand-alone retail was modeled with metal-frame walls, while the older and new vintage were modeled with heavy mass walls.

ESM Appendix B reports additional construction properties for each of the 10 prototypes.

2.3.6 Envelope insulation

EnergyPlus models each envelope assembly (e.g., roof or wall) as a series of spatially uniform layers. We represent each insulated frame (roof joists or wall studs with cavity insulation) as a layer of continuous insulation with thermal resistance equal to that of the insulated frame. Parallel-path calculation of the equivalent thermal resistance R_e of an insulated frame is detailed in ESM Appendix C.

2.3.7 Thermostat schedule

ESM Appendix B.3 describes the thermostat schedules used in our California and U.S. simulations in all vintages for the single-family home, medium office, large office, and stand-alone retail.

2.4 Building energy simulation

2.4.1 Simulation tools

All simulations were performed with EnergyPlus (EnergyPlus 2003), a program designed to model the energy uses of a building, including those for cooling, heating, and ventilation. We used jEPlus (jEPlus 2015), a parametric EnergyPlus simulation manager, to vary wall albedo, roof albedo, and building orientation. All simulations were run on the jEPlus Simulation Server, or JESS, cloud service (JESS 2015).

2.4.2 Parametric analysis

For California, we developed 96 residential building prototypes (2 building categories × 16 California climate zones × 3 vintages) and 384 commercial building prototypes (8 building categories × 16 California climate zones × 3 vintages). Similarly, we developed 270 residential building prototypes (2 building categories × 3 heating systems × 15 U.S. climate zones × 3 vintages) and 360 commercial building prototypes (8 building categories × 15 U.S. climate zones × 3 vintages) for the United States.

Each building prototype was modeled without considering shading or reflection by neighboring structures or trees. We parametrically varied wall and roof albedos to assess changes in annual building cooling, heating, and fan energy consumptions. We simulated the following scenarios for each building category, climate zone, and vintage:

(a) **Base case**: base wall albedo 0.25, and base roof albedo 0.10 (residential) or 0.20 (commercial). These base values represent albedos typical of walls and roofs in existing buildings.

(b) **Modified wall cases**: a series of alternate albedos (0.10, 0.40, and 0.60) for the modified walls, leaving roof albedo unchanged. This was done for each of the 15 wall combinations in Table 3.

(c) **Modified roof cases**: a series of alternate albedos for the roof, leaving wall albedo unchanged. In residential prototypes, the alternate albedos for the roof were 0.25, 0.40, and 0.60; in commercial prototypes, they were 0.10, 0.25, 0.40, and 0.60.

Each scenario was simulated once with the building's long axis oriented east-west and again with it oriented north-south. Thus, for a given location and vintage there were 98 simulations per residential prototype [(1 base case + 3 alternative roof albedos + 3 alternative wall albedos × 15 wall combinations) × 2 building orientations] and 100 simulations per commercial prototype [(1 base case + 4 alternative roof albedos + 3 alternative wall albedos × 15 wall combinations) × 2 building orientations].

Table 3. List of simulated wall combinations, taken 1, 2, 3, or 4 walls at a time.

Number of walls modified	Possible wall combinations
1	North (N), East (E), South (S), West (W)
2	NE, ES, EW, NS, NW, SW
3	NES, NEW, ESW, NSW
4	NESW

Therefore, in California there were 96 residential prototypes × 98 simulations per residential prototype = 9,408 residential simulations, and 384 commercial prototypes × 100 simulations per commercial prototype = 38,400 commercial simulations, for a total of 47,808 California simulations. For the U.S. there were 270 residential prototypes × 98 simulations per residential prototype = 26,460 residential simulations, and 360 commercial prototypes × 100 simulations per commercial prototype = 36,000 commercial simulations, for a total of 62,460 U.S. simulations.

2.4.3 Weather files

ESM Appendix A.3 describes the weather files used in the California and U.S. simulations.

2.5 Degree days and annual solar radiation

Cooling degree days at 18°C (CDD18C) and heating degree days at 18°C (HDD18C) can be used to predict cooling load and heating load, respectively (EIA 2017). Cool-surface energy savings also depend on solar radiation since changes in cooling and heating loads induced by raising albedo are proportional to incident sunlight. Section 3.2 shows annual CDD18C, annual HDD18C, and annual global horizontal solar radiation computed from the weather files used in the California and U.S. simulations.

Note that in this study the term "solar radiation" always means solar energy per unit area.

2.6 Monthly and seasonal daily solar radiation by surface

To understand how daily solar radiation varies by location, season, and orientation, the PVWatts Calculator (NREL 2017) was used to compute for each California and U.S. representative city the monthly and seasonal average values of daily solar radiation incident on a horizontal roof or on a north, east, south, or west exterior wall. We will refer to these five exterior envelope surfaces—roof, north wall, east wall, south wall, and west wall—as building "facets".

ESM Appendix D details for each simulated location in California and U.S. the monthly and seasonal daily solar radiation intercepted by the five facets. ESM Appendix D also shows for each facet the ratio of daily solar radiation received in winter to that received in summer.

2.7 Energy, peak power, pollution, and energy cost savings

2.7.1 Site energy savings

Consider a building prototype representing a building category, vintage, and location simulated with a given orientation (long axis north-south or east-west). Let E_{c}, E_{h}, and E_{f} represent annual whole-building cooling, heating, and fan site electricity uses, and let G_{h} represent annual whole-building heating site natural gas—hereafter, simply "gas"—use, each term evaluated in the base case (i.e., with wall and roof albedos set to prototype-specific base values). When the albedo of the roof or the albedo of one or more walls is raised to an alternate value, the annual whole-building cooling site electricity savings (e_{c}), heating site electricity *penalty* (e_{h}), fan site electricity savings (e_{f}), and heating site gas *penalty* (g_{h}) are calculated respectively as

$$e_{\mathrm{c}} = E_{\mathrm{c,base}} - E_{\mathrm{c,alternate}}\ , \tag{1}$$

$$e_{\mathrm{h}} = E_{\mathrm{h,alternate}} - E_{\mathrm{h,base}}\ , \tag{2}$$

$$e_{\mathrm{f}} = E_{\mathrm{f,base}} - E_{\mathrm{f,alternate}}\ , \tag{3}$$

and

$$g_{\mathrm{h}} = G_{\mathrm{h,alternate}} - G_{\mathrm{h,base}}\ , \tag{4}$$

where the subscript "alternate" refers to one of the alternate cases of a prototype (see Section 2.4.2) and the subscript "base" refers to the base case of the same prototype.

2.7.2 Source energy savings

The annual whole-building HVAC (heating + fan + cooling) source energy savings is calculated as

$$h_{\mathrm{HVAC}} = s_{\mathrm{e}} \times (e_{\mathrm{c}} + e_{\mathrm{f}} - e_{\mathrm{h}}) - s_{\mathrm{g}} \times g_{\mathrm{h}}\ , \tag{5}$$

where s_{e} is a state-specific site-to-source conversion factor for electricity and s_{g} is a non-regional site-to-source conversion factor for natural gas. These site-to-source conversion factors (ESM Table E-1 in ESM Appendix E) were obtained from the Source Energy and Emissions Analysis Tool, or SEEAT (GTI 2017). The tool uses current and previous eGRID databases[2] to determine state-specific rates of source energy consumption, greenhouse gas (GHG) emission, and criteria air pollutant emission per unit site electricity or site fuel (natural gas, oil, or propane) used. (Hereafter we will refer to both greenhouse gases and criteria air pollutants simply as "pollutants".) The electricity factors incorporate transmission losses and the gas factors include distribution losses.

2.7.3 HVAC peak power demand reduction

In this study, we define peak-demand hours as those between 12:00 and 18:00 local time (LT) on weekdays (Monday to Friday), June through September. For any given peak-demand hour i, the whole-building site HVAC peak power demand reduction is calculated as

$$d_{\mathrm{HVAC},i} = \frac{(e_{\mathrm{c},i} + e_{\mathrm{f},i} - e_{\mathrm{h},i})}{1\ \mathrm{hour}}, \tag{6}$$

where $e_{\mathrm{c},i}$, $e_{\mathrm{f},i}$, and $e_{\mathrm{h},i}$ are the peak-demand hour whole-building site cooling energy savings, fan energy savings, and electric heating energy penalty, respectively. Let T be the number of peak-demand hours in a year. The annual-average HVAC peak power demand reduction, $d_{\mathrm{HVAC,annual}}$, is calculated by averaging the HVAC power demand over all annual peak-demand hours:

$$d_{\mathrm{HVAC,annual}} = \frac{\sum_{i=1}^{T} d_{\mathrm{HVAC},i}}{T}. \tag{7}$$

2.7.4 Emission savings

The annual whole-building reduction in emission of pollutant a is calculated as

$$p_a = f_{\mathrm{e},a} \times (e_{\mathrm{c}} + e_{\mathrm{f}} - e_{\mathrm{h}}) - f_{\mathrm{g},a} \times g_{\mathrm{h}}\ , \tag{8}$$

[2] The Emissions & Generation Resource Integrated Database (eGRID) is a data source that provides characteristics (e.g., net generation, emission rates, and resource mix) of nearly all electric power generated in the United States (eGRID 2014).

where site electricity emission factor $f_{e,a}$ is the mass of pollutant emitted by power plants per unit of site electricity consumed, and site gas emission factor $f_{g,a}$ is the mass of pollutant emitted by the building's furnace per unit of site gas consumed. This study considers reductions in emission of carbon dioxide (CO_2), carbon dioxide equivalent[3] (CO_2e), nitrogen oxides (NO_x), and sulfur dioxide (SO_2). The emission factors of these four pollutants are listed in ESM Table E-2 (for site electricity) and in ESM Table E-3 (for site gas). These emission factors were also obtained from SEEAT and incorporate transmission and distribution losses.

2.7.5 Energy cost savings

Annual whole-building HVAC energy cost savings are calculated as

$$c = z_{\mathrm{e}} \times (e_{\mathrm{c}} + e_{\mathrm{f}} - e_{\mathrm{h}}) - z_{\mathrm{g}} \times g_{\mathrm{h}} , \tag{9}$$

where z_{e} and z_{g} are the state-specific annual average prices of electricity and gas, respectively. These prices are also dependent on type of building (residential or commercial). The annual average electricity and gas prices used in the study are reported in ESM Table E-4. These values are the state-average prices charged to residential and commercial customers in 2015 (EIA 2016a, EIA 2016b).

2.7.6 Savings intensity

The intensity (rate per unit of modified surface area) of site energy, source energy, emission, or energy cost savings j is calculated as

$$j'' = j/A_{\mathrm{m}} , \tag{10}$$

where A_{m} is the total surface area modified. For example, if the east and west walls were modified, A_{m} is the sum of the east and west net wall areas.

2.7.7 Mean savings and savings intensity over two building orientations

Each savings or savings intensity calculated using Eqs. (1) through (10) is for a single building orientation (long axis east-west or north-south). Two-orientation mean savings are calculated as

$$j_{\mathrm{mean}} = (j_{\mathrm{EW}} + j_{\mathrm{NS}})/2 , \tag{11}$$

[3] Carbon dioxide equivalent (CO_2e) is a measure that allows for greenhouse gas emissions other than CO_2 to be expressed in terms of CO_2 based on their global warming potential (GWP) relative to CO_2. Thus, emissions expressed as CO_2e represent the GWP of all greenhouse gases expressed in terms of CO_2 (SBT 2017).

where EW and NS refer to the long axis of the building running east-west and north-south, respectively. Two-orientation mean savings intensity is calculated as

$$\mathrm{j}''_{\mathrm{mean}} = (j_{\mathrm{EW}} + j_{\mathrm{NS}})/(A_{\mathrm{m,EW}} + A_{\mathrm{m,NS}}). \tag{12}$$

2.8 Savings database

For each prototype and building orientation, the simulations included the base case, modified wall cases, and modified roof cases described in Section 2.4.2. These simulations were used to calculate for each prototype the annual whole-building savings in site energy, source energy, emission, energy cost, and site HVAC peak power demand using Eqs. (1) to (9). All saving intensities were calculated using Eq. (10). Savings and savings intensities averaged over the two building orientations were computed using Eqs. (11) and (12), respectively.

Savings and savings intensities for every simulated prototype were compiled in a database that is detailed in ESM Appendix F and provided as a comma-separated values file in the electronic supplementary material.

3 Results

3.1 Overview

We focus on a subset of the California and U.S. simulations to evaluate the effects of raising wall albedo. We use the single-family home to represent residential buildings, and the medium office building and stand-alone retail store to represent commercial buildings.

Cool roofing products for pitched roofs on homes (e.g., concrete tiles, clay tiles, and high-performance asphalt shingles) are typically rated with an aged albedo around 0.40, while cool roofing products for low-slope roofs on commercial buildings are typically rated with an aged albedo of at least 0.60 (Sleiman et al. 2011). In the case of walls, an aged albedo of at least 0.60 can be currently obtained with light-colored paints (Chen et al. 2018). We assume that a conventional residential roofing product (e.g., a dark asphalt shingle) has an aged albedo of about 0.10; that a conventional commercial roofing product (e.g., a dark-gray membrane) has an aged albedo of about 0.20; and that a conventional wall coating (e.g., a dark to medium color paint) has an aged albedo of about 0.25. Thus, in these case studies, we present cool-wall savings from increasing wall albedo by 0.35 (to 0.60 from 0.25) in both residential and commercial buildings, and cool-roof savings from increasing roof albedo by 0.30 (to 0.40 from 0.10) in residential buildings and by 0.40 (to 0.60 from 0.20) in commercial buildings.

We compare cool-wall savings to those provided by cool roofs, and explore how the cool-wall savings vary by building location, building vintage, and combination of walls modified. Finally, we investigate whether the sum of savings from walls modified one at a time equals the savings from modifying the same set of walls simultaneously.

All savings and penalties shown here average values from the two building orientations (long axis east-west or north-south). Values by orientation are available in the savings database.

3.2 Degree days and annual solar radiation

Figure 1 and Figure 2 show CDD18C, HDD18C, and annual global horizontal solar radiation calculated from the weather files used in the California and U.S. simulations.

In California (Figure 1), the warmest climate zone is CACZ15 (Imperial; 2,700 CDD18C), which represents the state's southeastern deserts. California climate zones located in the state's Central Valley (CACZs 11, 12, 13, and 14) have warm summers as well as cool winters. The coastal climates zones (CACZs 1, 2, 3, and 5) have cool climates and have high HDD18C. The coldest climate zone is CACZ 16 (Mount Shasta; 3,400 HDD18C), which represents the mountainous regions of the state.

California has limited variation in annual global horizontal solar radiation, ranging from 1.45 MWh/m² (Arcata; CACZ 1) to 2.1 MWh/m² (China Lake; CACZ 14).

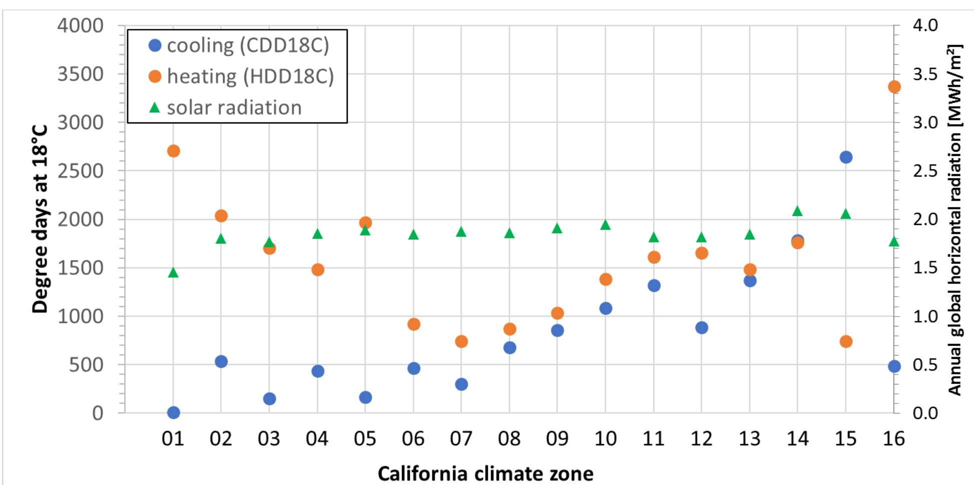


Figure 1. Cooling degree days at 18 °C (CDD18C), heating degree days at 18 °C (HDD18C), and annual global horizontal solar radiation by California climate zone, computed from CZ2010 weather files.

In the U.S. (Figure 2) the U.S. climate zone with the most CDD18C is 2B (Phoenix; 2,800 CDD18C) followed by USCZ 1A (Miami; 2,500 CDD18C). All U.S. climate zones from 3C onward had fewer than 1,000 CDD18C. HDD18C increased with U.S. climate zone number, ranging from 140 HDD18C (Miami; USCZ 1A) to 7,200 HDD18C (Fairbanks; USCZ 8).

USCZs 3B (El Paso) and 4B (Albuquerque) receive the most sunlight, getting nearly 2.1 MWh/m² annually. USCZ 8 (Fairbanks) receives the least sunlight (0.95 MWh/m²).

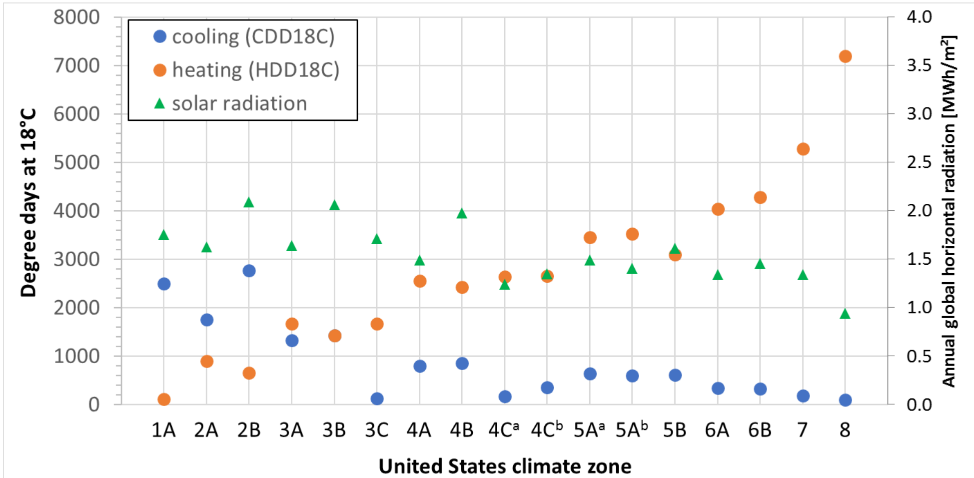


Figure 2. Cooling degree days at 18°C (CDD18C), heating degree days at 18°C (HDD18C), and annual global horizontal solar radiation by United States climate zone, computed from TMY3 weather files. Superscripts *a* and *b* designate weather files used in the current study for residential or commercial prototypes, respectively.

3.3 Cooling, heating, fan, and HVAC source energy savings intensities by climate zone and facet in the new single-family home

The single-family home is the most common building type in California and the U.S., and has the most floor area nationwide (Section 6.7.5 in Rosado 2016). The current section reports the annual source energy cooling, fan, and HVAC savings intensity and heating penalty intensity in the *new* single-family home by California and U.S. climate zone upon individually increasing by 0.35 (to 0.60 from 0.25) the albedo of the north, east, south, or west wall, or increasing by 0.30 (to 0.40 from 0.10) the albedo of the roof. Similar trends were observed for savings in the *older* and *oldest* single-family homes.

3.3.1 California savings intensities by climate zone

Figure 3 shows annual source energy cooling savings intensity, heating penalty intensity, fan savings intensity, and HVAC savings intensity for the new single-family home in California.

In every California climate zone, raising wall or roof albedo reduced cooling and fan energy uses and increased heating energy use. However, each facet (wall or roof) yielded cooling plus fan savings that exceeded the heating penalty, producing HVAC savings in every California climate zone. CACZs 1 (Arcata) and 16 (Mount Shasta) had the smallest HVAC savings intensities. Arcata exhibited the smallest cooling savings intensities and had the fewest cooling degree days (8 CDD18C). Arcata (2,700 HDD18C) and Mount Shasta (nearly 3,400 HDD18C) had the most heating degree days and large heating penalty intensities.

The greatest HVAC savings intensities were in CACZs 6 (Long Beach), 7 (San Diego), and 15 (Imperial). The first two (CACZs 6 and 7) had few CDD18C and HDD18C compared to the other California locations. However, low requirements for roof and wall insulation in the single-family home helped make HVAC savings intensities in CACZs 6 and 7 larger than those in other California climate zones. Specifically, the new single-family prototypes in CACZs 6 and 7 were simulated with less wall insulation than in all other CACZs; the wall-assembly thermal resistance—hereafter, simply "wall thermal resistance"—in CACZs 6 and 7 was R-15.4 (15.4 h·ft^2·°F/BTU) or RSI-2.71 (2.71 m^2·K/W) (ESM Table C-2), which is 79% of the R-19.6 (RSI-3.45) value that was used in all other CACZs (R-15.4 / R-19.6 = 79%). The roof-assembly thermal resistance —hereafter, simply "roof thermal resistance"—in CACZs 6 and 7 was R-30.3 (RSI-5.34) (ESM Table C-3), or 66% of the R-46.2 (RSI-8.14) value used in many other CACZs (4, 8-16).

The third location (CACZ 15) had the most CDD18C (2,650) and fewest HDD18C (740); it is also one of the most sunlit places in California (Figure 2). Its warm and sunny climate contributed to high HVAC savings intensities.

3.3.2 California savings intensities by facet

Changes in HVAC energy use are proportional to changes in heat conducted through the building envelope, which in turn scale with changes in wall solar heat gain. Wall solar heat gain depends on wall direction. Thus, all else being equal, we expect the modified wall that receives the most solar radiation to yield the greatest changes in HVAC energy use intensity.[4]

Of all four walls, the north wall yielded in all California climate zones the lowest annual cooling and fan source energy savings intensities (Figure 3a,c) because it received the least solar radiation. For example, consider CACZ 13 (Fresno), in which the north wall provided cooling savings intensity 9.5 MJ/m^2, or 42% of that of the east wall (22.5 MJ/m^2). ESM Table D-17 indicates that the summer daily solar radiation on the north wall is 1.89 kWh/m^2, which is 44% of that on the east wall (4.33 kWh/m^2). During winter, the north wall again receives the least sunlight, yielding the smallest heating penalty intensity (Figure 3b).

In all California climate zones, the annual cooling and fan source energy savings intensities from the roof were generally as small as those from the north wall. The roof and north-wall savings intensities were in turn smaller than those of the east, south, and west walls. However, the roof (if assumed to be horizontal) was the facet that received the most summer daily solar radiation (ESM Tables D-5 to D-20). The key is that the thermal resistance of the wall is less than half that of the roof. For example, in CACZs 4 and 8-16, the thermal resistance of the wall

[4] In some prototypes and locations, the east wall yielded the greatest changes in HVAC energy use while the west wall received the most sunlight. We do not have a clear explanation for this phenomenon.

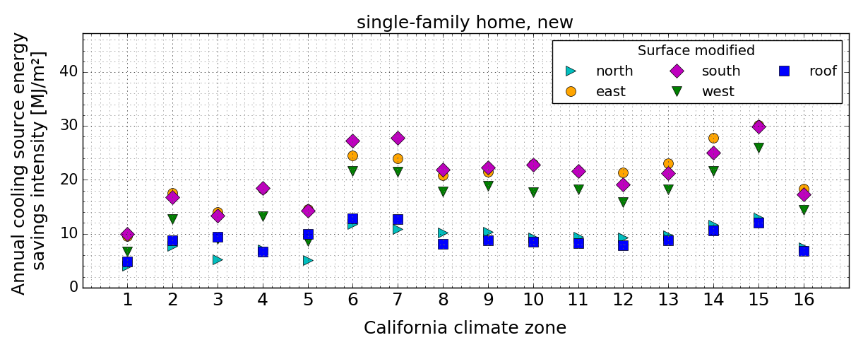
is R-19.6 (RSI-3.45), or 42% of the roof thermal resistance in these climate zones (ESM Table C-4).

Heating penalty intensities of the roof were once again smaller than those of the east, south, and west walls, and similar to those of the north wall.

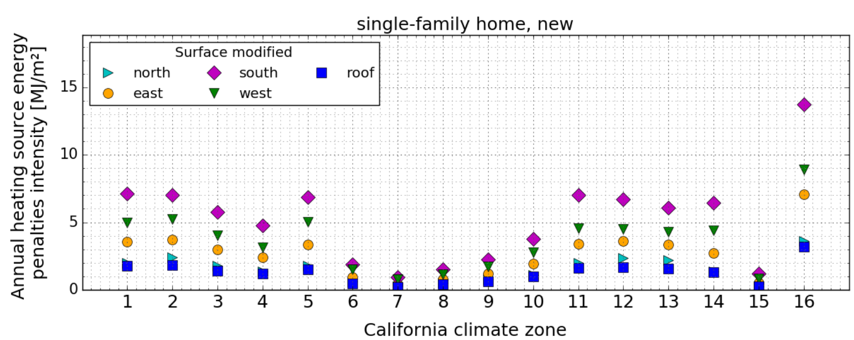
The wall that receives the most daily solar radiation in summer is the west wall, followed by the east wall (ESM Table D-1). However, in many California climate zones the south wall yielded the greatest cooling and fan savings intensities. In the remaining California climate zones, the greatest cooling and fan energy savings intensities were from the east wall. The savings intensities from the west wall were 70% to 90% of those from the east wall.

In all California climate zones, the south wall received more solar radiation in winter than any of the other facets, including the roof. Thus, in all locations, the south wall yielded heating penalty intensities greater than those from any of the other surfaces (ESM Table D-3). In most locations, the south wall received more sunlight during winter than in summer; in some, the south wall's heating penalty was near as large as its cooling savings. The facet yielding the largest HVAC savings intensity varied by location but was usually either the east wall or south wall (Figure 3d).

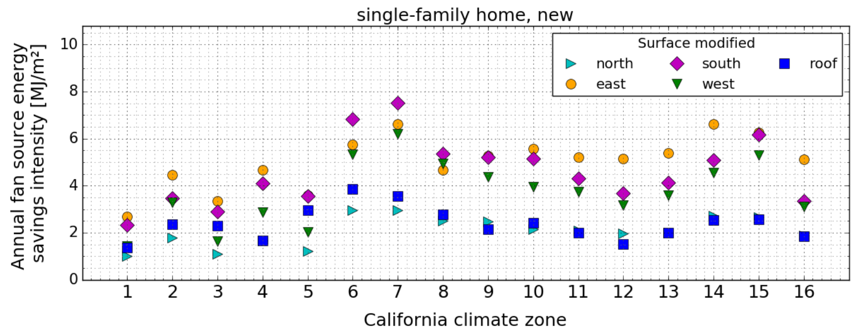
(a)



(b)



(c)



(d)

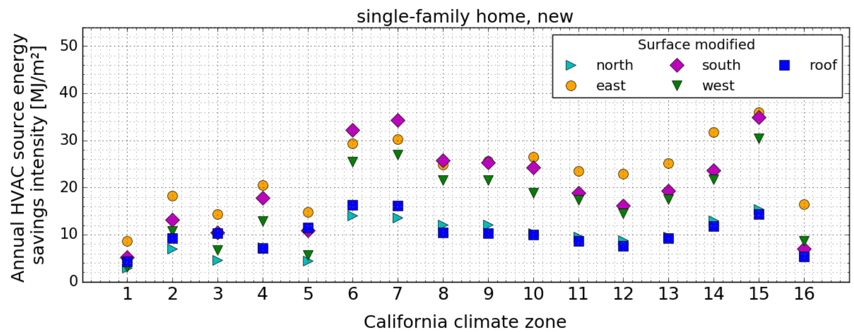


Figure 3. Annual source energy savings and penalty intensities of the new single-family home by facet and California climate zone. The plots show intensities of (a) cooling savings, (b) heating penalties, (c) fan savings, and (d) HVAC savings.

3.3.3 U.S. savings intensities by climate zone

First, note that in the new single-family home, the wall thermal resistance in USCZs 1A, 2A, 2B, 3A, and 4B was R-11.5 (RSI-2.03) (ESM Table C-5), or 71% of the R-16.3 (RSI-2.87) value that was used in all other U.S. climate zones. The roof thermal resistance in USCZs 1A, 2B, and 3A was R-27.6 (ESM Table C-6), which is 85% of the R-32.4 (RSI-5.71) that was used in USCZs 2A, 3B, 3C, 4B, and 5B or 73% of the R-37.6 (RSI-6.62) that was used in USCZs 4A, 4C, 5A, 6A, 6B, 7, and 8.

Figure 4 shows annual source energy cooling savings intensity, heating penalty intensity, fan savings intensity, and HVAC savings intensity for the new single-family home in the U.S. In every U.S. climate zone, raising wall or roof albedo reduced cooling and fan energy uses (Figure 4a,b) and increased heating energy use (Figure 4b). However, 9 out of 15 U.S. climate zones (USCZs 1A, 2A, 2B, 3A, 3B, 3C, 4A, 4B and 5A) experienced annual HVAC source energy savings from each of the five facets (Figure 4d). Among these nine U.S. climate zones, USCZ 2B (Phoenix) benefited the most from cool walls and cool roofs, attaining significantly greater HVAC savings intensities than all others. USCZ 2B had the most CDD18C (2,800), received the most solar radiation, and had few HDD18C (700). It was also one of the locations with the lowest wall and roof thermal resistances. USCZ 1A (Miami) had the second largest HVAC savings; it had many CDD18C (2,500) and the fewest HDD18C (100) (Figure 2). Wall and roof thermal resistances in Miami were as low as those in Phoenix. Within these nine U.S. climate zones, USCZ 5A (Peoria) had the smallest HVAC savings; its ratio of HDD18C to CDD18C was about 5, and its wall and roof thermal resistances were higher than in the remaining eight USCZs. USCZs 4C (Seattle), 5B (Boise), and 6A (Burlington) received small HVAC savings from some facets and HVAC penalties from the other facets. USCZs 6B (Helena), 7 (Duluth), and 8 (Fairbanks) experienced HVAC penalties from all five facets (Figure 4d). All these USCZs with HVAC penalties had significantly more HDD18C than CDD18C. Fairbanks, AK (USCZ 8) had the fewest CDD18C (50) and the most HDD18C (7,100). Still, USCZ 8 experienced HVAC penalties very similar to those in USCZ 6B (Helena), which had 42% fewer HDD18C (4,150). However, the magnitudes of all HVAC savings and penalties in USCZs 4C, 5B, 6A, 6B, 7, and 8 were half or less than those in USCZs 1A (Miami), 2B (Phoenix), 3A (Memphis), and 3B (El Paso) (Figure 4d).

3.3.4 U.S. savings intensities by facet

Of the four walls, the north yielded in all U.S. climate zones the lowest cooling and fan savings intensities (Figure 4a,c) because it received the least solar radiation. For example, let us consider USCZ 2B (Phoenix), in which the north wall provided annual cooling source energy savings intensity 30 MJ/m², or 41% of that from the east wall (68 MJ/m²). ESM Table D-23 indicates that the summer daily solar radiation on the north wall was 1.95 kWh/m², which is 47% of that on the east wall (4.13 kWh/m²). During winter, the north wall again received the least solar radiation, leading to the smallest heating penalty intensity (Figure 4b).

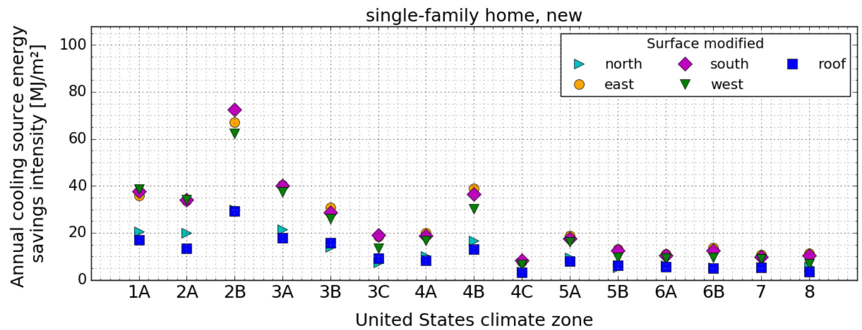
The cooling savings intensities from the roof were never greater than those from any of the four walls, and in most cases were less than those from the east, south, and west walls. However, in all U.S. climate zones, the roof (if assumed to be horizontal) was the facet that received the most summer daily solar radiation (ESM Tables D-21 to D-37). The key again is that the thermal resistance of the roof is at least twice that of the wall. For example, in USCZs 1A, 3B, and 3A, the thermal resistance of the wall is R-11.5 (RSI-2.03), which is 42% of the roof thermal resistance in these locations (ESM Table C-7). The heating penalty intensity from the roof was also smaller than those from the east, south, and west walls, and slightly greater than those from the north wall.

The wall that received the most daily solar radiation in summer varied by U.S. climate zone, but was either east or west (ESM Table D-2). In some locations, the south wall yielded the greatest cooling savings intensity; in the rest, it was the east or west wall. Cooling savings intensities from the east, south, and west walls were very similar in all locations.

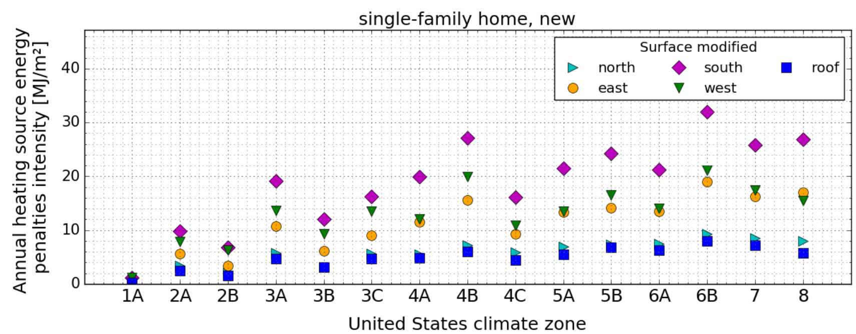
In all U.S. climate zones, the south wall received more solar radiation during winter than any of the other facets, including the roof (ESM Table D-2). Thus, in all locations the south wall yielded heating penalty intensities greater than those from any of the other facets (Figure 4b).

In most U.S. locations, the south wall received at least as much daily solar radiation in winter as in summer (ESM Table D-4). Additionally, from USCZ 4C onward, each location had significantly more HDD18C than CDD18C. Thus in cold climates the south wall's heating penalty intensity was up to twice its cooling savings intensity (Figure 4a,b).

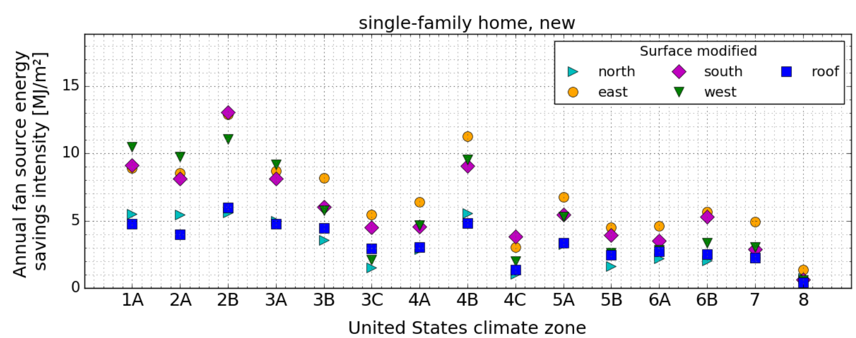
(a)



(b)



(c)



(d)

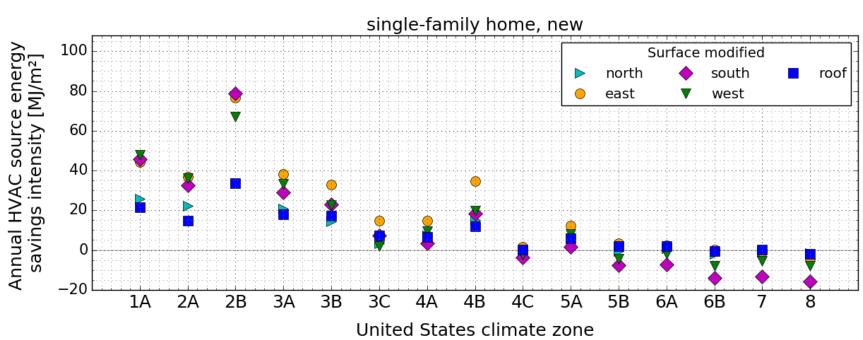


Figure 4. Annual source energy savings and penalty intensities of the new single-family home by U.S. climate zone. The plots show intensities of (a) cooling savings, (b) heating penalties, (c) fan savings, and (d) HVAC savings.

3.4 HVAC savings by vintage and climate zone in the single-family home, medium office building, and stand-alone retail store

This section details annual HVAC source energy savings for the single-family home, medium office, and stand-alone retail[5] upon (a) increasing the albedo of all four walls simultaneously by 0.35 (to 0.60 from 0.25) or (b) increasing the albedo of the roof to 0.40 from 0.10 (single-family home) or to 0.60 from 0.20 (medium office and stand-alone retail). Each metric is compared by vintage and by climate zone. Analogous HVAC energy cost, CO_2e, NO_x, SO_2, and peak power demand savings are summarized here and detailed in ESM Appendix G.

3.4.1 California HVAC source energy savings

Figure 5 shows annual HVAC source energy savings intensity by vintage and by California climate zone for the single-family home (Figure 5a), medium office (Figure 5b), and stand-alone retail (Figure 5c).

In the single-family home (Figure 5a) the increase in roof albedo (0.30) was 86% of that in wall albedo (0.35). In each vintage, the thermal resistance of the roof was much greater than that of the wall; the ratio (roof to wall) was 2.7 in the older and oldest vintages and 1.5 – 2.4 in the new vintage (ESM Table C-4). Differences between roof and wall thermal resistances help explain why the cool-wall savings intensity was often at least twice that from a cool roof.

In the single-family home (Figure 5a), the thermal resistance of the wall in the new vintage was 3.4 times that in the oldest vintage, while the cooling efficiency in the new vintage was 1.4 times that in the oldest vintage. If the heating penalty is small compared to the cooling savings we would expect the cool-wall HVAC savings intensity in the oldest single-family home to be about $3.4 \times 1.4 = 4.8$ times that of the new home. This estimate matches well with what we observe in Figure 5a and report in ESM Table G-1, where the cool-wall savings intensity in the oldest vintage was about 5 times that in the new vintage. The HVAC savings intensity in the older single-family home was about 2.5 times that in the new single-family home (ESM Table G-2).

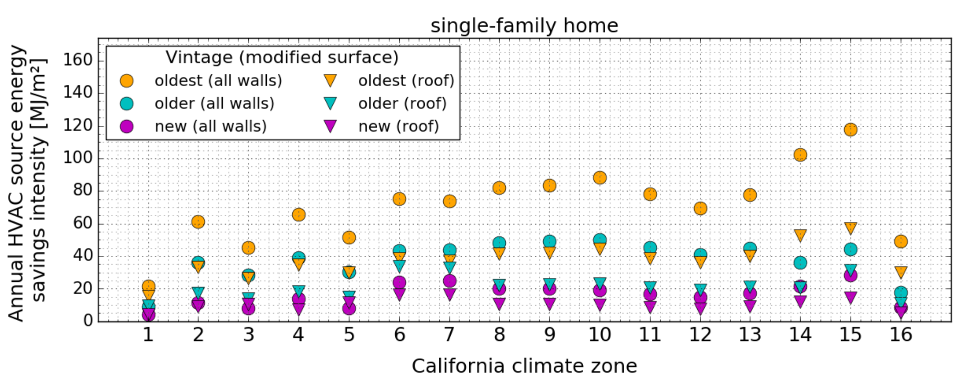
[5] We have omitted all results for the new stand-alone retail building in USCZ 1A (Miami) because modifying the albedo of its rear wall yielded unrealistically large changes in annual fan energy use.

The medium-office savings (Figure 5b) were based on increasing the wall albedo by 0.35 (to 0.60 from 0.25) or increasing the roof albedo by 0.40 (to 0.60 from 0.20). Thus, the increase in roof albedo was 14% greater than the increase in wall albedo. The thermal resistance of the roof in the oldest medium office was 1.2 – 1.4 times that of the wall in CACZs 2–5 and 8–13, but 2.0 – 2.6 times that of the wall in the remaining CACZs (1, 6–7, and 14–16) (ESM Table C-4). In these California climate zones with a high ratio of roof thermal resistance to wall thermal resistance, the cool-wall savings intensity exceeded that from a cool roof (Figure 5b).

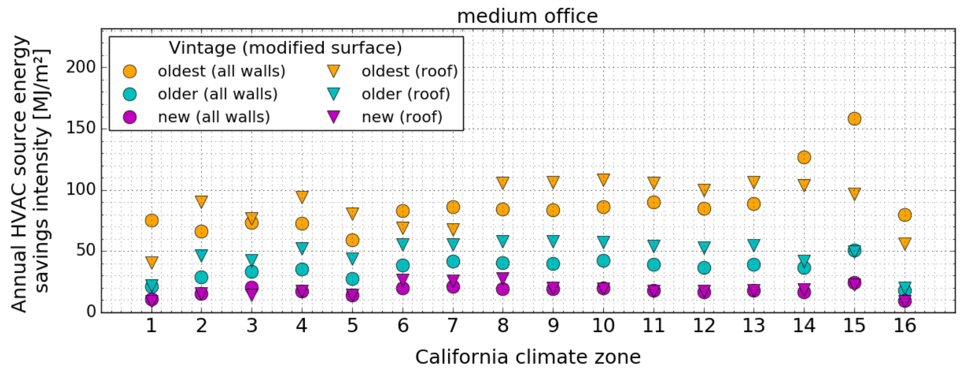
In the medium office (Figure 5b), the new vintage to oldest vintage ratio of wall thermal resistance varies by location but ranges from 3.8 to 6.4. Additionally, the cooling efficiency in the new vintage was only 1.1 times that in the oldest vintage. Thus, we would expect the cool-wall savings intensity in the oldest single-family home to be between 4.2 (3.8 × 1.1) and 7.0 (6.4 × 1.1) times that of the new medium office. This estimate matches well with what we observe in Figure 5a and report in ESM Table G-1, where the cool-wall savings intensity in the oldest vintage was on average 5.2 times that in the new vintage. The cool-wall savings intensity in the older medium office was on average 2.0 times that in the new medium office (ESM Table G-2).

In the stand-alone retail, the cool-wall savings intensity throughout California in the oldest vintage was on average 5.8 times that in the new vintage (Figure 5c; ESM Table G-1), while the cool-wall savings intensity in the older vintage was on average 2.6 times that in the new vintage (Figure 5c; ESM Table G-2). The oldest-to-new and older-to-new savings intensity ratios for the stand-alone retail were greater than those for the medium office even though the wall thermal resistances in the stand-alone retail and medium office were very similar (identical in most cases). That is because the air conditioner efficiency in the stand-alone retail increased 23% (to 3.49 from 2.84) between the old vintages (i.e., oldest and older) and the new vintage, while the corresponding increase in the medium office was only 5.0% (to 3.96 from 3.78) (ESM Table B-7).

(a)



(b)



(c)

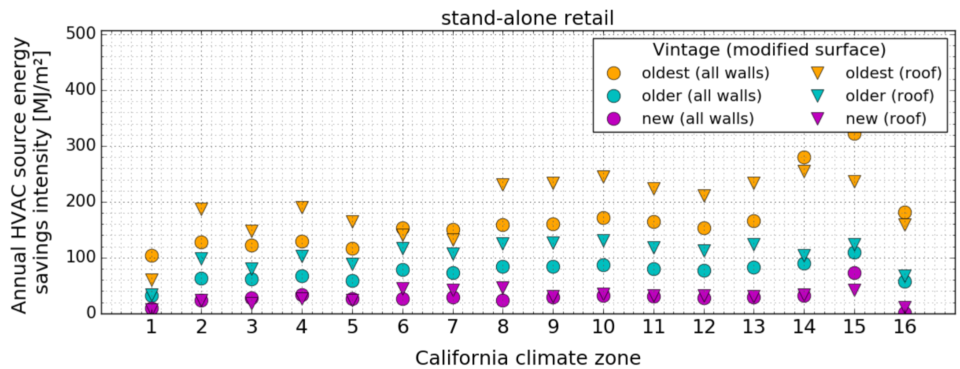


Figure 5. Annual HVAC source energy savings intensity by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) stand-alone retail. The plots compare the savings intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

The fractional savings (ratio of absolute savings to base value) in energy, energy cost, and emissions were influenced not only by the absolute savings but also by the energy consumed in the base case. When comparing cool walls to a cool roof, the differences in fractional savings were driven by the envelope characteristics (e.g., differences in surface albedo change and in insulation) as well as by the envelope geometry (e.g., ratio of roof area to net wall area).

Figure 6 shows annual HVAC source energy fractional savings by vintage and by California climate zone for the single-family home (Figure 6a), medium office (Figure 6b), and stand-alone retail (Figure 6c). For the single-family home (Figure 6a), CACZ 7 (San Diego) had the greatest cool-wall and cool-roof fractional savings in all vintages, reaching up to 25% (oldest vintage) when all walls were made cool and 8.0% (oldest vintage) when the roof was made cool. Low requirements for roof and wall insulation helped make the annual HVAC source energy savings intensity in CACZ 7 larger than that in the other CACZs. San Diego also had fewer CDD18C and HDD18C than other locations, requiring lower-than-average baseline conditioning energy consumption. CACZs 14 (China Lake) and 15 (Imperial) had the greatest annual HVAC source energy savings intensity, but lower than average annual HVAC energy fractional savings;

fractional savings in CACZs 14 and 15 were up to 12% (oldest vintage) when all walls were made cool and up to 4.0% (oldest vintage) when the roof was made cool.

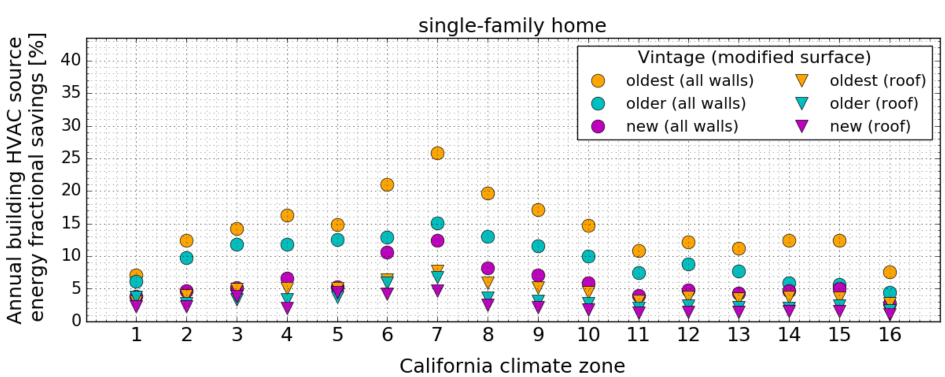
In the single-family home, the annual HVAC source energy savings intensity from cool walls was about 2 times that from a cool roof (Figure 5a). However, the fractional savings from the walls were 2.2 – 3.3 times that from the roof. The wall-to-roof ratio of fractional savings was greater than the corresponding ratio of savings intensity because the net wall area exceeds the roof area. From ESM Table B-6, we gather that the net wall area is 1.6 times the roof area. Thus, the ratio of wall savings intensity to roof savings intensity multiplied by the net wall-to-roof area ratio is 2 × 1.6 = 3.2. This adjusted wall-to-roof savings ratio is similar to the ratio of 2.2 to 3.5 observed for HVAC fractional savings in Figure 6a.

For the medium office (Figure 6b), we saw once again that CACZ 15 (Imperial), the location with highest savings intensity, yielded fractional savings that were close to the California average. Fractional savings in CACZ 15 were 3.7% (oldest vintage) when all walls were made cool and 3.0% (older and oldest vintage) when the roof was made cool.

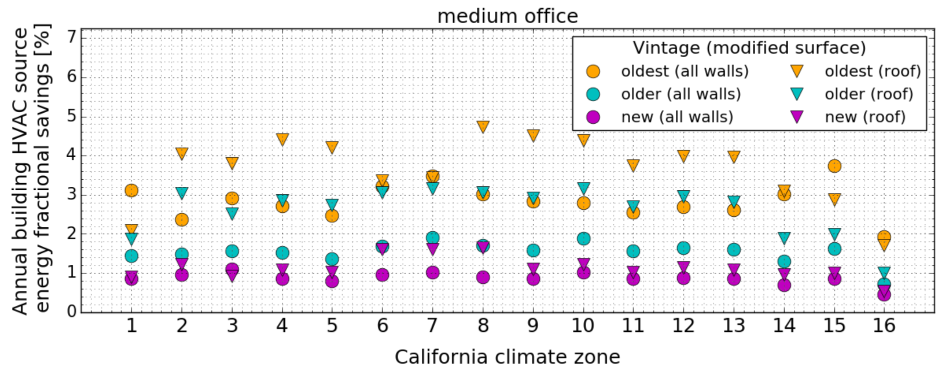
When analyzing savings intensities in the medium office (Figure 5b), we observed that in most California climate zones and vintages, the savings intensity from the roof was slightly greater than that from the walls. The roof-to-wall ratio for fractional savings (Figure 6b) was higher than that for the savings intensity, in part because the modified roof area is 1.3 times the modified net wall area. Although the medium office is three stories high, its large window area (ratio of window to gross wall area is 0.33) gives it more roof area than net wall area.

In the case of stand-alone retail (Figure 6c), the roof-to-wall ratios of HVAC fractional savings were even greater than those observed in the medium office because the stand-alone retail is a single-story building with a large footprint (2,290 m²), and has more than twice as much roof area as net wall area (ratio of roof area to net wall area is 2.1) (ESM Table B-6).

(a)



(b)



(c)

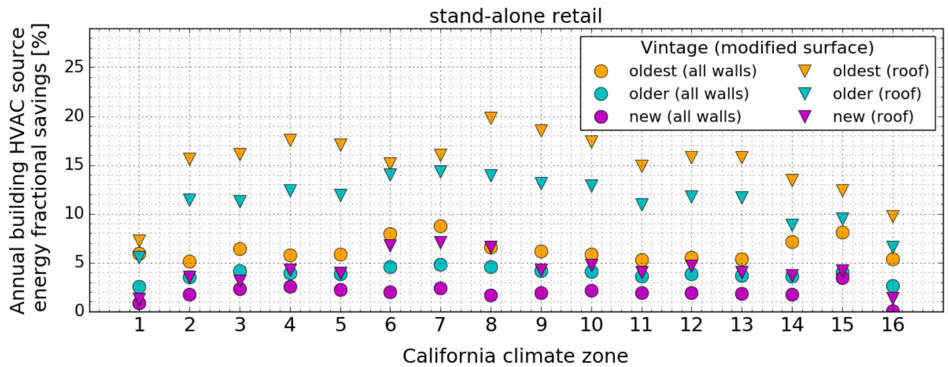


Figure 6. Annual HVAC source energy fractional savings by vintage and by California climate zone for the (a) single-family home, (b) medium office, and (c) stand-alone retail. The plots compare fractional savings from increasing the albedo of all walls by 0.35 to those from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.4.2 California HVAC energy cost, pollutant emission, and peak power demand savings

ESM Appendix E provides the conversion factors used to calculate emission of air pollutants (CO_2, CO_2e, NO_x, and SO_2) (ESM Table E-2 and ESM Table E-3) and energy cost (ESM Table E-4). In the coldest climates (CACZs 1 and 16), cool walls in the single-family home and stand-alone retail yielded small HVAC source energy savings but sometimes induced small increases in pollutant emissions because gas was used for heating while electricity was used for cooling. Cool walls reduced whole-building annual pollutant (CO_2e, NO_x, SO_2) emissions by -1.5 – 24% in single-family homes, 0.3 – 3.8% in medium offices, and 0.0 – 10% in stand-alone retail stores. Whole-building peak power demand reductions were 3.0 – 43% in single-family homes, 0.6 – 5.8% in medium offices, and 1.0 – 16% in stand-alone retail stores. Whole-building annual HVAC energy cost reductions were 4.0 – 27% in single-family homes, 0.5 – 3.8% in medium offices, and 0.0 – 8.5% in stand-alone retail stores.

ESM Appendix G details the complete analysis of HVAC energy cost, pollutant emission, and peak power demand savings in California.

3.4.3 U.S. HVAC source energy savings

First, note that in all locations except USCZ 8 (Fairbanks), the annual daily solar radiation received by the roof was 1.7 to 2.0 times the four-wall average solar radiation.

Figure 7 shows annual HVAC source energy savings intensity by vintage and by U.S. climate zone for the single-family home (Figure 7a), medium office (Figure 7b), and stand-alone retail (Figure 7c). In the single-family home (Figure 7a) the increase in roof albedo (0.30) was 86% of that in wall albedo (0.35). Additionally, in each vintage, the thermal resistance of the roof was much greater than that of the wall (roof-to-wall ratio 1.7 – 3.4) (ESM Table C-7). Hence, although the solar radiation incident on the roof is about twice the four-wall average, the wall savings intensity was often comparable to the roof savings intensity.

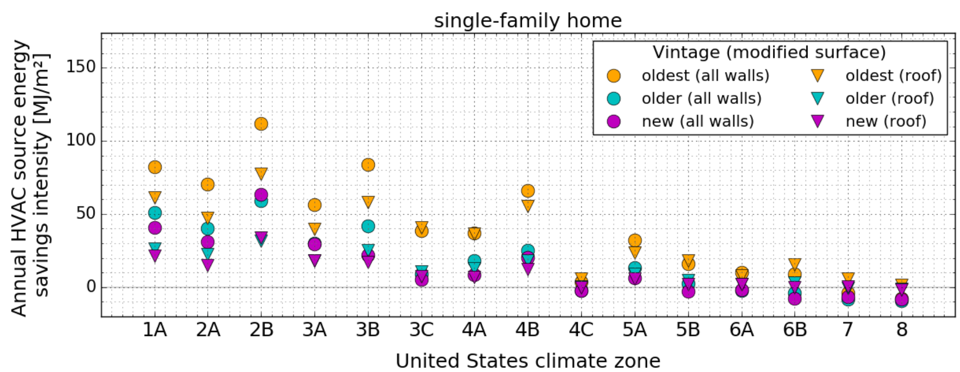
In the single-family home (Figure 7a), differences in cool-wall savings intensities between vintages are related to variations in wall thermal resistance and cooling equipment efficiency. For example, in USCZ 1A (Miami), the thermal resistance of the wall in the new vintage was 1.8 times that in the oldest vintage, and the ratio of cooling equipment efficiency (new vintage to oldest vintage) was 1.3. If the heating penalty is small compared to the cooling savings we would expect the cool-wall HVAC savings intensity in the oldest single-family home to be about 1.8 × 1.3 = 2.3 times that of the new home. This estimate matches well with what we observe in Figure 7a, where the cool-wall savings intensity from the oldest single-family home in USCZ 1A was about 2.1 times that of the new vintage. This ratio varied by U.S. location, but on average the savings intensity in the oldest home was 3.0 times that in the new home (ESM Table G-3). The savings intensity in the older single-family home was on average 1.3 times that of the new home (ESM Table G-4).

Savings in the medium office (Figure 7b) were attained by raising the wall albedo by 0.35 (to 0.60 from 0.25) and by raising the roof albedo by 0.40 (to 0.60 from 0.20). Thus, the increase in roof albedo was 1.14 times that of walls. The thermal resistance of the roof in the oldest medium office was about 2.0 to 2.4 times that of the wall (ESM Table C-7). Here again, even though the roof radiation is about twice the four-wall average, the wall savings intensity typically equaled or exceeded the roof savings intensity (Figure 7b).

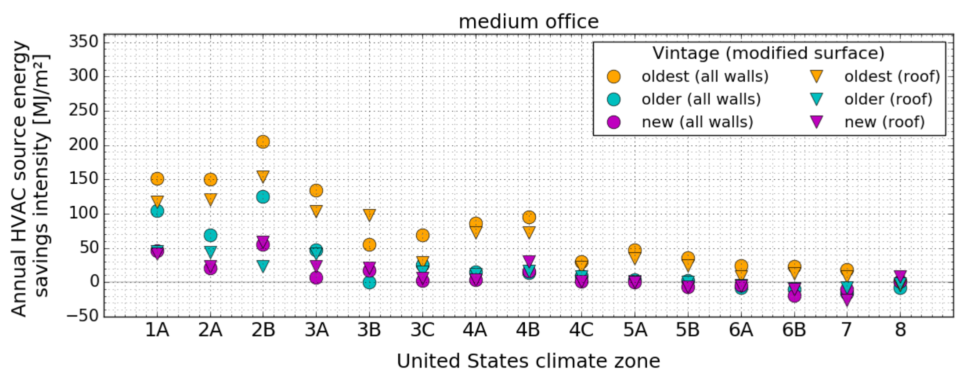
In the medium office (Figure 7b), the thermal resistance of the wall in the new vintage was 1.5 to 3.0 times that in the oldest vintage, while the cooling efficiency in the new vintage was 1.1 to 1.2 times that in the oldest vintage. For example, in USCZ 2B (Phoenix) the new-to-oldest vintage ratio of wall thermal resistance was 1.9 and that of cooling equipment efficiency was 1.1. If the heating penalty is small compared to the cooling savings we would expect the savings intensity from cool walls in the oldest medium office to be 1.9 × 1.1 = 2.1 times that in the new medium office. This estimate is similar to what we observe in Figure 7b where the cool wall savings intensity from the oldest vintage was 1.8 times that of the new vintage. This ratio varied by U.S. location, but on average, the savings intensities from the oldest home were 1.5 to 8 times that of the new home in USCZs 1A – 4B and 5A, the zones experiencing positive savings in both vintages. The savings intensity in the older medium office was on average 4.1 times that in the new medium office in those locations that yielded savings in both vintages (ESM Table G-4).

In the stand-alone retail (Figure 7c), differences between cool-wall and cool-roof savings intensities stemmed from variations in albedo change, thermal resistance, and solar radiation. However, the magnitude of the savings (or penalty) intensity in the new vintage sometimes exceeded that in the oldest vintage. For example, in USCZ 2B (Phoenix), the savings intensity when all walls were made cool in the new vintage was 410 MJ/m², which is about 2.2 times that in the oldest vintage because the wall thermal resistance in the new vintage was half of that in the oldest vintage. The oldest stand-alone retail was simulated with metal frame walls, while the new stand-alone retail was simulated with heavy mass walls. In warm climates such as USCZ 2B the wall assembly in the new stand-alone retail was uninsulated heavy mass. Thus in some locations the wall thermal resistance in the new stand-alone retail was less than that in the oldest vintage. Note that the older stand-alone retail was also simulated with heavy mass walls.

(a)



(b)



(c)

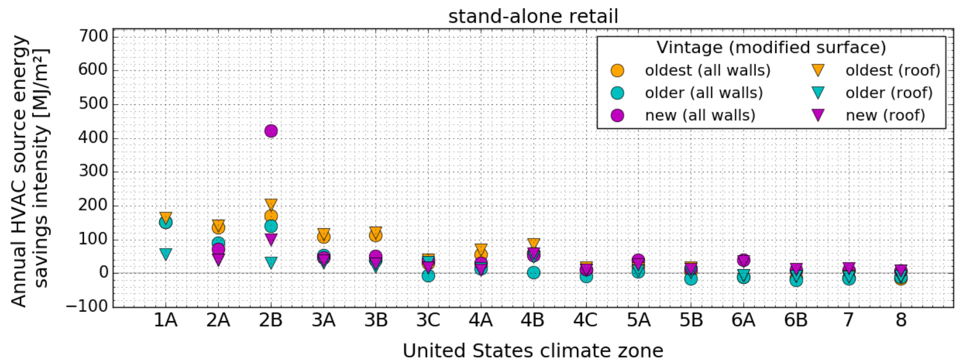


Figure 7. Annual HVAC source energy savings intensity by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) stand-alone retail. The plots compare the savings intensity from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

Figure 8 shows fractional savings by vintage and by U.S. climate zone for the single-family home (Figure 8a), medium office (Figure 8b), and stand-alone retail (Figure 8c). For the single-family home (Figure 8a), the highest value of cool-wall fractional savings was 8.3% (oldest, USCZ 3B, El Paso), followed in descending order by 7.7% (oldest, USCZ 2B, Phoenix), 7.5% (oldest and new, USCZ 1A, Miami), and 6.7% (oldest, USCZ 2A, Houston). The highest value of cool-roof fractional savings was obtained from the oldest vintage in USCZ 3C (San Francisco), followed in descending order by the oldest vintages in USCZs 1A (Miami), 3B (El Paso), 2B (Phoenix), and 4B (Albuquerque). In U.S. climate zones 4C (Salem), 5B (Boise), 6A (Burlington), and 6B (Helena), cool walls in the oldest home yielded fractional savings of 0.5% to 2.0% while cool walls in the new home produced fractional penalties of 0.2% to 1.2%.

In the single-family home, the wall-to-roof ratio of fractional savings was always greater than 1.0, and often up to 2.0 (Figure 7a), because the net wall area exceeds the roof area. For example, consider the oldest home in USCZ 2B (Phoenix). The cool-wall savings intensity was about 1.4 times that from the roof. From ESM Table B-6, we gather that the net wall area is 1.6 times the roof area. Thus, the ratio of cool-wall savings intensity to cool-roof savings intensity multiplied by the net wall-to-roof area ratio is $1.4 \times 1.6 = 2.2$, close to the ratio of about 2.3 observed for the oldest home in USCZ 2B (Figure 8a).

For the medium office (Figure 8b), USCZ 2B (Phoenix) experienced the highest savings intensities for roof and walls across all vintages. However, the greatest fractional savings (4.5%) were yielded by cool walls on the oldest medium office in USCZ 3C (San Francisco). Although USCZ 3C had small HVAC source energy savings intensities for all vintages, it produced large fractional savings because base energy use was low.

In most U.S. climate zones and vintages, cool-wall savings intensity slightly exceeded cool-roof savings intensity in the medium office (Figure 7b). However, the roof area in the medium office exceeds the net wall area (roof area to net wall area ratio is 1.3). Since fractional savings scale with surface area modified, those from the roof were often similar to or greater than those from the walls (Figure 8b). Cool-wall and cool-roof fractional savings in the oldest vintage exceeded than those in the older and new vintages, and were about 3.5% from USCZ 1A (Miami) to 3A (Memphis). The oldest vintage attained cool-wall and cool-roof fractional savings in all locations, but they diminished as the U.S. climate zone number increased. In the new medium office, cool walls yielded fractional savings of up to 2% in USCZs 1A (Miami) and 2B (Phoenix), but generated fractional penalties of up to 1.6% between USCZs 5B (Boise) and 7 (Duluth).

The roof-to-wall ratio of fractional savings in the stand-alone retail (Figure 8c) was even greater than that in the medium office because the stand-alone retail is a single-story building with a large footprint (2,290 m^2), and its roof area is more than twice its net wall area (ratio is 2.1) (ESM Table B-6).

In the new stand-alone retail, cool walls produced fractional savings in all U.S. climate zones, with values up to 11% in USCZ 2B (Phoenix) and nearly 5.0% in USCZ 2A (Houston). The older stand-alone retail experienced fractional penalties of 1.0% in USCZ 5B (Boise) and smaller fractional penalties in USCZs 3C (San Francisco), 4C (Salem), 6A (Burlington), 6B (Helena), 7 (Duluth), and 8 (Fairbanks).

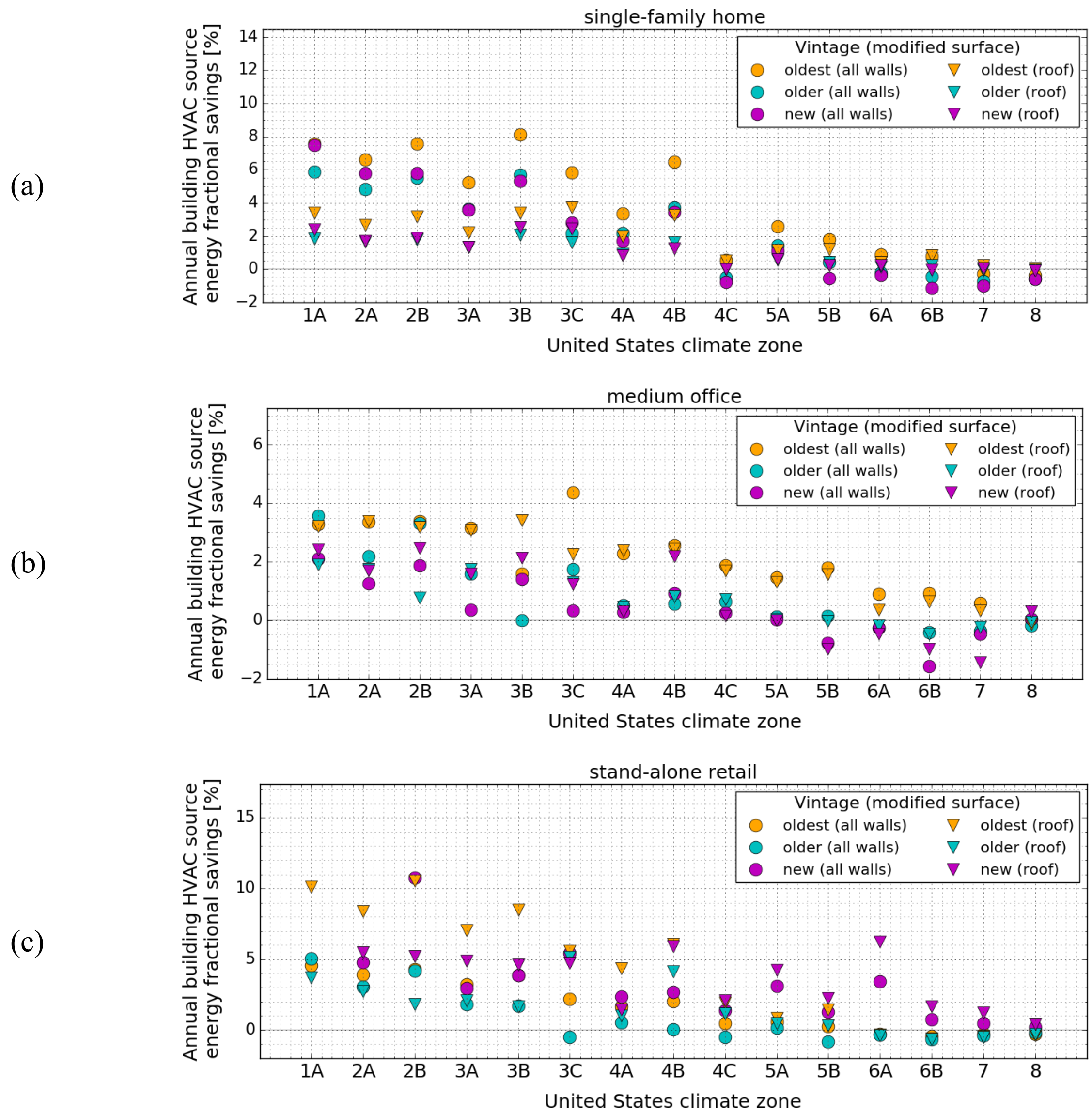


Figure 8. Annual HVAC source energy fractional savings by vintage and by U.S. climate zone for the (a) single-family home, (b) medium office, and (c) stand-alone retail. The plots compare the fractional savings from increasing the albedo of all walls by 0.35 to that from increasing the roof albedo by 0.30 (residential) or 0.40 (commercial).

3.4.4 U.S. HVAC energy cost, pollutant emissions, and peak power demand savings

In warm U.S. climates—zones 1A (Miami, FL) through 4B (Albuquerque, NM)—cool walls reduced whole-building annual HVAC energy cost 1.8 – 8.3% in single-family homes, 0.3 – 4.6% in medium offices, and 0.5 – 11% in stand-alone retail stores. Whole-building annual pollutant emission reductions in warm U.S. climates were -4.5 – 13% in single-family homes, -

0.4 – 6.3% in medium offices, and -4.5 – 12% in stand-alone retail stores. Cool walls also yielded annual whole-building HVAC energy cost savings and pollutant emissions reductions in some cold U.S. climates—zones 4C (San Francisco, CA) through 7 (Duluth, MN)—for certain building categories and vintages.

Across the U.S., cool walls reduced whole-building peak power demand 5.0 – 22% in single-family homes, 0.4 – 4.9% in medium offices, and 0.3 – 8.2% in stand-alone retail stores.

ESM Appendix G details the complete analysis of HVAC energy cost, pollutant emissions, and peak power demand savings across the U.S.

4 Discussion

4.1 Wall orientations yielding greatest annual HVAC source energy savings

All walls within a given prototype have the same thermal resistance. If each modified wall undergoes the same albedo change, differences by orientation in savings or penalty intensities are driven by the differences in absorbed solar radiation. For example, consider a building in the northern hemisphere. In summer, the east and west walls receive the most solar radiation, followed in descending order by the south wall and north wall. Under clear skies, the south wall will receive more beam sunlight in winter than in summer because the sun is lower, the wall's minimum beam incidence angle is smaller, and the wall is exposed to more hours of direct (beam) illumination.

4.1.1 California

The north wall always yielded the smallest annual cooling source energy savings intensity (hereafter, "cooling savings intensity") and smallest annual heating source energy penalty intensity (hereafter, "heating penalty intensity"). The south wall typically generated the greatest cooling savings intensity, followed closely by the west and east walls. However, the south wall also typically yielded the highest heating penalty intensities.

The wall providing the greatest annual HVAC source energy savings intensity (hereafter, "HVAC savings intensity") varied by prototype and climate. In the commercial prototypes, it was usually the west wall, followed by the east wall. In the residential prototypes, it was usually the south wall, but, the east-, south-, and west-wall values were very similar.

4.1.2 United States

As in California, the north wall in the single-family home always generated the smallest cooling savings intensity and smallest heating penalty intensity, leading to the smallest annual HVAC savings or penalty intensity. Cool walls yielded cooling savings in every U.S. climate zone. The wall orientation with the greatest cooling savings intensity varied by location, but was either the east, south, or west wall. However, these three wall orientations typically yielded similar cooling savings intensities. Cool walls induced annual heating penalties in every U.S. climate zone, but south-wall heating penalty intensities were significantly higher than those from the other walls.

Each wall in the single-family home yielded annual HVAC savings from USCZ 1A (Miami) to USCZ 4B (Albuquerque). In USCZs 6B (Helena), 7 (Duluth), and 8 (Fairbanks), each wall produced an HVAC penalty or essentially no change in annual HVAC source energy use. The south wall yielded annual HVAC energy penalties from USCZ 4C (Seattle) to USCZ 8 (Fairbanks).

4.2 Vintages and geometries yielding greatest annual HVAC source energy savings

4.2.1 California

In California, the oldest vintage always yielded the greatest cool-wall savings intensity, followed by the older vintage, because walls in the older and oldest vintages were built with substantially less insulation than required in new construction. The older and oldest vintages were also simulated with HVAC efficiencies that comply with 10+ year old building codes. These older and oldest vintage buildings represent over 75% of the current residential stock and about 70% of the commercial stock in California. Cool-wall HVAC savings intensities in the new vintage prototypes were still significant and comparable to those from cool roofs.

Whole-building cool-wall savings scale with net wall area and therefore with building height. Even prototypes with a large window-to-wall area ratio such as medium and large offices benefited from cool walls since these were tall multi-story buildings with large net wall areas.

4.2.2 United States

For most building categories in the U.S., the oldest vintage yielded the largest cool wall annual HVAC energy savings or penalty intensity. In buildings where the wall type and wall construction varied by vintage, such as stand-alone retail, the vintage yielding the greatest annual HVAC energy changes varied by U.S. climate zone.

Representative cities for some U.S. climate zones are in states that mandate 10 to 13 year old building codes for new construction(ESM Table B-1). In these U.S. climate zones, the new prototypes were simulated with HVAC efficiencies comparable to those used in the older and oldest vintages. The prototypes in these U.S. climate zones were also usually assigned lower envelope thermal resistances than in the other zones. Thus in U.S. climate zones that follow 10+ year old building codes the annual HVAC source energy savings from the new vintage were often close to those from the older vintage.

4.3 Cool-wall savings versus cool-roof savings

Recall that in the California and U.S. case studies, the simulated increase in wall albedo (0.35) was 0.05 (16.7%) more than that in residential roof albedo (0.30), and was 0.05 (12.5%) less than the increase in commercial roof albedo (0.40). Differences between cool-wall and cool-roof energy savings intensities were in part due to these variations in albedo increase. Other differences stem from solar trends. In summer, the zenith sun is high, and on a clear day the roof receives more daily solar radiation than any of the four walls. In winter, the zenith sun is low, so the roof receives less solar radiation on a clear winter day than on a clear summer day. Also, since in the northern hemisphere the sun peaks in the south, the south wall receives more solar radiation on a clear winter day, when the beam incidence angle is small, than on a clear summer day, when the beam incidence angle is large.

4.3.1 California

In the older and oldest vintages of all prototypes, the east, south, and west walls yielded greater annual HVAC source energy savings intensities than did the roof. In these vintages, wall thermal resistance was significantly lower than roof thermal resistance. Hence, while in summer the roof received more daily solar radiation than any of the walls, the roof savings intensity was in some cases as small as that of the north wall, the facet that received the least solar radiation in summer. Cool wall HVAC savings intensity exceeded cool-roof savings intensity in some of new vintage prototypes.

In prototypes with a large ratio of roof area to net wall area, the whole-building annual HVAC source energy savings from raising the albedo of all four walls were smaller than those from increasing roof albedo. The two retail prototypes and the sit-down restaurant had the largest ratios of roof area to net wall area, which were at least 2. In these three prototypes, the whole-building savings from the four walls were smaller than those from the roof in all three vintages. Conversely, buildings with a small ratio of roof area to net wall area (e.g., the single-family home and apartment building) typically yielded whole-building wall savings that exceeded the roof savings. In the oldest vintage, the whole-building wall savings in the single-family home were up to 3.0 times those of the roof. In the new vintage, buildings with small ratio of roof area to net wall area still had whole-building wall savings that were equal to or greater than those from the roof.

4.3.2 United States

In all vintages, the magnitude of annual HVAC source energy changes from the east, south, and west walls always exceeded that from the roof. In locations with warm climates (USCZ 1 to USCZ 4B), the east, south, and west walls in the single-family home yielded greater annual HVAC source energy savings intensities than those from the roof; savings intensities from the roof were similar to those from the north wall. In the U.S., the ratio of roof thermal resistance to wall thermal resistance and the ratio of solar radiation intercepted by the roof to that received by each wall also varied strongly by location. Thus, differences between east, south, or west wall HVAC savings intensities and that at the roof varied widely across the United States. In cold climates the annual HVAC source energy penalty intensities from the north, east, and west walls were similar to those from the roof.

In the warm climates, raising the albedo of all four walls yielded a four-wall-average annual HVAC source energy savings intensity comparable to that from increasing roof albedo. Differences between cool-wall and cool-roof HVAC savings intensities varied by building category, vintage, and location. In cold climates [USCZs 5B (Boise) to 8 (Fairbanks)], the changes (savings or penalties) in annual HVAC source energy use intensity from the north, east, and west walls were similar to those from the roof. In these cold climates, the south wall yielded an annual HVAC source energy penalty intensity greater than that from any other facet.

As in California, the ratio of whole-building savings from increasing the albedo of all four walls to those from increasing the albedo of the roof was influenced by the ratio of roof area to net wall area. For example, in prototypes with a small ratio of roof area to net wall area ratio, such as single-family homes, whole-building savings from cool walls were up to 2.5 times those from a cool roof.

4.4 Modifying combinations of walls

ESM Appendices H.1 and H.2 compare in California and the United States, respectively the savings from modifying a group of walls simultaneously to the sum of the savings from modifying the walls one at a time.

While the annual cooling savings were usually additive, the annual heating penalties and fan savings were sometimes non-additive. We delved into a few analyses that considered (a) auto-sized versus fixed-size HVAC systems and (b) hourly energy uses of each HVAC component.

The additive tests indicate that it is worth exploring further this matter, since for most prototypes and in most locations, annual HVAC energy savings were close to being fully additive. If savings from individual walls are in fact additive, this will simplify estimation of cool wall savings for any of the 15 possible wall combinations.

5 Conclusions and recommendations

This paper presents an exhaustive study of the effects of cool walls in individual buildings in all California and U.S. climate zones. The work investigated how cool walls may lead to changes in site energy use, source energy use, energy cost, pollutant emissions, and HVAC peak power demand. As we expected, the magnitude of savings and penalties from cool walls depends on key factors including climate, wall construction, wall orientation, building orientation, and HVAC efficiency. The influence of each of these factors on cool-wall savings and penalties was investigated by simulating (a) 31 different climate zones across California and U.S.; (b) 3 different building vintages (oldest, older, and new) that followed building codes adopted in each location and vintage; (c) 15 different wall combinations; and (d) 2 different building orientations.

5.1 California

Cool walls yielded annual HVAC source energy, energy cost, pollution emission, and peak power demand savings in all 16 California climate zones. Cool-wall savings intensities were greatest in climate zones 14 (China Lake) and 15 (Imperial), which have long and warm cooling seasons coupled with short and mild heating seasons. The smallest cool-wall savings intensities were in California climate zones 1 (Arcata) and 16 (Mount Shasta), the two coldest locations in the state.

Cool walls benefitted the oldest vintage prototypes significantly more than the older and new vintage prototypes; savings in the oldest vintage were usually 3.0 – 6.0 times those in the new vintage while savings in the older vintage were typically 2.0 – 3.0 times those in the new vintage. Cool walls in the oldest single-family home yielded annual HVAC source energy fractional savings up to 25% (CACZ 7, San Diego). Across all vintages, cool walls reduced whole-building annual HVAC energy use 3.0% to 25% in single-family homes, 0.5% to 3.7% in medium offices, and 0.0% to 9.0% in stand-alone retail stores; lowered annual HVAC energy cost 4.0 – 27% in single-family homes, 0.5 – 3.8% in medium offices, and 0.0 – 8.5% in stand-alone retail stores; decreased annual pollutant (CO_2e, NO_x, and SO_2) emissions -1.5 – 24% in single-family homes, 0.3 – 3.8% in medium offices, and 0.0 – 10% in stand-alone retail stores; and reduced peak power demand 3.0 – 43% in single-family homes, 0.6 – 5.8% in medium offices, and 1.0 – 16% in stand-alone retail stores. Source energy use, energy cost, and emission savings in the oldest vintage were generally three to six times those in the new vintage. The cool-wall savings from the oldest vintage are important since these buildings represent over 60% of California's stock.

While the solar radiation incident on walls is typically less than that received by the roof, past and present California building codes prescribe more insulation in roofs than in walls. Hence, the source energy use, energy cost, and emission savings intensities from cool walls are comparable to those from cool roofs. In buildings with substantially more net wall area than roof area, the whole-building savings from four cool walls were often significantly greater than those from a cool roof. In the single-family home, which had a high ratio of net wall area to roof area, the ratio of cool-wall to cool-roof whole-building HVAC source energy savings was 1.5 – 3.5. The medium office and stand-alone retail had low ratios of net wall area to roof area, with cool-wall to cool-roof whole-building HVAC source energy savings ratios of 0.40 – 1.0 and 0.20 – 0.85, respectively. Thus, the differences in savings between cool walls and cool roofs are highly dependent on two building characteristics: (a) roof and wall insulation, and (b) ratio of net wall area to roof area.

The south wall always yielded the largest heating penalty intensity; however, it also produced a large cooling savings intensity. The south-wall HVAC savings intensity was similar to those from the east wall and west wall, which in turn were always exceeded that from the north wall.

Therefore, the east, south, and west walls are most relevant for cool-wall adoption in California. Cool walls will also reduce HVAC peak power demand across the state.

5.2 United States

In the U.S., climate zone 2B (Phoenix) benefitted the most from cool walls because (a) it has a warm climate and (b) the state of Arizona follows 10+ year old building codes. USCZs 1A (Miami), 2A (Houston), 3A (Memphis), 3B (El Paso), 3C (San Francisco), 4A (Baltimore), and 4B (Albuquerque) also yielded cool-wall savings from all vintages. The remaining U.S. climate zones are generally colder and less sunny, with small savings or small penalties from cool walls.

As in California, the oldest vintage yielded the largest cool wall savings and penalties. This is important since in most U.S. locations the oldest vintage buildings represent at least 60% of the stock. For example, in residential buildings, the savings from the oldest vintage were 2.0 – 3.0 times that of the new vintage and savings from the older vintage were typically 1.2 – 2.0 times that of the new vintage. In warm U.S. climate—zones 1A (Miami, FL) through 4B (Albuquerque, NM)—cool walls in all vintages reduced whole-building annual HVAC source energy use 2.0% — 8.5% in single-family homes, 0.0% – 4.2% in medium offices, and -0.5% to 5% in stand-alone retail stores; lowered annual HVAC energy cost 1.8 – 8.3% in single-family homes, 0.3 – 4.6% in medium offices, and 0.5 – 11% in stand-alone retail stores; and decreased annual pollutant emissions -4.5 – 13% in single-family homes, -0.4 – 6.3% in medium offices, and -4.5 – 12% in stand-alone retail stores. Cool walls also yielded small annual HVAC source energy savings in cold United States climate zones—4C (San Francisco, CA) through 7 (Duluth, MN) —in some building categories and vintages. Across the U.S., cool walls reduced peak power demand 5.0 – 22% in single-family homes, 0.4 – 4.9% in medium offices, and 0.3 – 8.2% in stand-alone retail stores.

The east, south, and west walls typically yielded similar savings intensities, which in turn were greater than those from the north wall. Additionally, the cool wall savings intensities of the east, south, and west walls were similar, and sometimes much greater than that of the cool roof. In warm U.S. climate zones [1A (Miami, FL) to 4B (Albuquerque, NM)], the ratio of whole-building cool-wall savings to whole-building cool roof savings was 1.1 to 3.0 in single-family homes, 0.20 to 1.9 in medium offices, and 0.30 to 2.1 in stand-alone retail.

This study demonstrated that in the U.S., all buildings of any vintage from USCZ 1A (Miami) to USCZ 4B (Albuquerque) would benefit from cool walls, especially on the east, south, and west facets. Cool walls will also reduce HVAC peak power demand across the nation.

5.3 Recommendations for future research

Future work should further investigate the additive nature of cool wall savings, examining those simulations in which the cool-wall savings were not additive.

The current study also provides the foundation for two new Codes and Standards Enhancement (CASE) initiatives—techno-economic policy assessments—to enhance California's Title 24 building energy efficiency standards. The first CASE initiative should evaluate the prescription of cool walls on both new and existing residential and commercial buildings across California. The second CASE initiative should consider expanding to additional climate zones a residential cool-roof retrofit requirement that currently applies in only 6 of California's 16 climate zones. The latter suggestion is motivated by our finding that increasing roof albedo benefits older (1980s) and oldest (pre-1980) vintage homes in all California climate zones.

Finally, the current study can serve as a roadmap for investigation of cool-wall benefits outside the United States.

Acknowledgements

This research was supported by the California Energy Commission under contract EPC-14-010, and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Thanks to Yi Zhang (Energy Simulation Solutions Ltd.) for assistance with the jEPlus Simulation Server (JESS), Joe Huang (White Box Technologies) for contributing weather files, and to Tianzhen Hong (Lawrence Berkeley National Laboratory) for troubleshooting EnergyPlus building models. Thanks also to Haley Gilbert (Lawrence Berkeley National Laboratory) for assisting with research management, and to George Ban-Weiss, Jiachen Zhang, and Arash Mohegh (University of Southern California) for discussions about modeling.

References

Abood AA. 2015. A comprehensive solar angles simulation and calculation using MATLAB. *International Journal of Energy and Environment* 6(4), 367-376. https://www.academia.edu/13809972/A_comprehensive_solar_angles_simulation_and_calculation_using_Matlab

Akbari H, Konopacki S, Pomerantz M. 1999. Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States. *Energy* 24, 391 – 407. https://doi.org/10.1016/S0360-5442(98)00105-4

Akbari H, Konopacki S. 2005. Calculating energy-saving potentials of heat-island reduction strategies. *Energy Policy* 33, 721 – 756. https://doi.org/10.1016/j.enpol.2003.10.001

ASHRAE. 2001. ANSI/ASHRAE*/IES Standard 90.1-2001—Energy Standard for Buildings Except Low-Rise Residential Buildings*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers. Atlanta, GA. https://www.ashrae.org/technical-resources/bookstore/standard-90-1

ASHRAE. 2002. ASHRAE Guideline 14-2002, Measurement of Energy and Demand Savings, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA. http://www.eeperformance.org/uploads/8/6/5/0/8650231/ashrae_guideline_14-2002_measurement_of_energy_and_demand_saving.pdf

Bhatia A, Mathur J, Garg V. 2011. Calibrated simulation for estimating energy savings by the use of cool roof in five Indian climatic zones. *Journal of Renewable Sustainable Energy* 3, 023108. http://dx.doi.org/10.1063/1.3582768

BCAP 2017. Code Status Maps. Building Codes Assistance Project (BCAP). Retrieved 2017-01 from https://bcapcodes.org/code-status/

Blum J. 2007. Roof insulation R-values for commercial buildings under ASHRAE and “above-code” standards. *RCI Interface*, 31-36. November 2007. Retrieved from http://rci-online.org/wp-content/uploads/2016/04/2007-11-blum.pdf

Boixo S, Diaz-Vicente M, Colmenar A, Castro MA. 2012. Potential energy savings from cool roofs in Spain and Andalusia. *Energy* 38, 425 – 438. https://doi.org/10.1016/j.energy.2011.11.009

Briggs RL, Lucas RG, Taylor ZT. 2003a. Climate Classification for Building Energy Codes and Standards: Part 1—Development Process. *ASHRAE Transactions*, 109, 109-121 https://search.proquest.com/docview/192522382

Briggs RL, Lucas RG, Taylor ZT. 2003b. Climate Classification for Building Energy Codes and Standards: Part 2—Zone Definitions, Maps, and Comparisons. *ASHRAE Transactions* 109, 122-130. https://search.proquest.com/docview/27811966

CEC. 1988. 1988 Building Energy Efficiency Standards. Publication CEC-400-1988-001, California Energy Commission, Sacramento, CA. Retrieved 2015-12-10 from http://www.energy.ca.gov/title24/standards_archive/

CEC. 2005. 2005 Building Energy Efficiency Standards for Residential and Nonresidential Buildings. Publication CEC-400-2006-015, California Energy Commission, Sacramento, CA. Retrieved 2015-12-10 from http://www.energy.ca.gov/title24/standards_archive/

CEC. 2015. California Building Climate Zone Areas. California Energy Commission, Sacramento, CA. Retrieved 2015-12-10 from http://www.energy.ca.gov/maps/renewable/building_climate_zones.html

CEC. 2016a. 2016 Nonresidential compliance manual. Publication CEC-400-2015-033-CMF, California Energy Commission, Sacramento, CA. Retrieved 2016-01 from http://www.energy.ca.gov/title24/

CEC. 2016b. 2016 Residential compliance manual. Publication CEC-400-2015-032-CMF, California Energy Commission, Sacramento, CA. Retrieved 2016-01 from http://www.energy.ca.gov/title24/

CEC. 2016c. 2016 Building Energy Efficiency Standards for Residential and Nonresidential Buildings. Publication CEC-400-2015-037-CMF, California Energy Commission, Sacramento, CA. Retrieved 2016-01 from http://www.energy.ca.gov/title24/

CEC. 2016d. 2016 Residential Alternative Calculation Method (ACM) Reference Manual. Publication CEC-400-2015-024-CMF-REV3, California Energy Commission, Sacramento, CA. Retrieved 2016-06 from http://www.energy.ca.gov/title24/

Chen S, Gilbert H, Truong M, Houzé de l'Aulnoit S, Zhang J, Ban-Weiss G, Levinson R, Destaillats H. 2018. Solar-reflective "cool" walls: Benefits, technologies, and implementation. Appendix J: Natural exposure of wall products (Task 4.2 report). Draft online at https://bit.ly/2D0vfYt

Comfort-Pro. 2015. What is the Life Expectancy of My HVAC System? [Blog post]. Posted March 12, 2015. Retrieved from https://www.comfort-pro.com/2015/03/what-is-the-life-expectancy-of-my-hvac-system/

Deru M, Field K, Studer D, Benne K, Griffith B, Torcellini P, Liu B, Halverson M, Winiarski D, Rosenberg M, Yazdanian M, Huang J, Crawley D. 2011. US Department of Energy commercial reference building models of the national building stock. Technical report NREL/TP-5500-46861, National Renewable Energy Laboratory, Golden, CO. Retrieved 2015-12 from http://energy.gov/eere/buildings/commercial-reference-buildings

EIA. 2009. Residential energy consumption survey (RECS) – public use microdata. U.S. Energy Information Administration Washington, DC. Retrieved 2015-12-10 from http://www.eia.gov/consumption/residential/data/2009/

EIA. 2012. Commercial Building Energy Consumption Survey (CBECS) – public use microdata. U.S. Energy Information Administration, Washington, DC. Retrieved 2016-09-01 from http://www.eia.gov/consumption/commercial/data/2012/

EIA. 2016a. Annual average retail price of electricity to ultimate customers by state, sector, and year. U.S. Energy Information Administration, Washington, DC. Retrieved from https://www.eia.gov/electricity/data.php#sales

EIA. 2016b. Annual natural gas price by state and year. U.S. Energy Information Administration, Washington, DC. Retrieved from https://www.eia.gov/naturalgas/data.cfm

EIA. 2017. Units and Calculators – Degree Days. U.S. Energy Information Administration, Washington, DC. Retrieved 2017-06-30 from https://www.eia.gov/energyexplained/index.cfm?page=about_degree_days

eGRID 2014. 2014 Emissions & Generation Resource Integrated Database (eGRID). U.S. Environmental Protection Agency (EPA). Retrieved from https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid

EnergyPlus. 2003. EnergyPlus version 8.5. Downloaded from https://energyplus.net/

Gao Y, Xu J, Yang S, Tang X, Zhou Q, Ge J, Xu T, Levinson R. 2014. Cool roofs in China: Policy review, building simulations, and proof-of-concept experiments. *Energy Policy* 74, 190 – 214. https://doi.org/10.1016/j.enpol.2014.05.036

Gentle, AR, Aguilar, JLC, Smith, GB. 2011. Optimized cool roofs: Integrating albedo and thermal emittance with R-value. *Solar Energy Materials and Solar Cells*, 95(12), 3207–3215. https://doi.org/10.1016/j.solmat.2011.07.018

Huang J, Hanford JW, and Yang F. 1999. Residential heating and cooling loads component analysis. LBNL-44636. Lawrence Berkeley National Laboratory, Berkeley CA. https://simulationresearch.lbl.gov/dirpubs/44636.pdf

Hunn BD. 2010. 35 Years of Standard 90.1. ASHRAE Journal, 52(3), 36-46, March 2010. Retrieved from https://www.ashrae.org/resources--publications/bookstore/90-1---celebrating-35-years-of-energy-efficiency

IECC. 2006. 2006 International Energy Conservation Code. International Code Consortium. January 2006. Retrieved from https://archive.org/details/gov.law.icc.iecc.2006

jEPlus. 2015. jEPlus v1.6.0 – An EnergyPlus simulation manager for parametrics. Downloaded 2015-12 from http://www.jeplus.org/wiki/doku.php

JESS. 2015. JESS – jEPlus Simulation Server. Downloaded 2015-12 from http://www.jeplus.org/wiki/doku.php

Levinson R. 2019. Using solar availability factors to adjust cool-wall energy savings for shading and reflection by neighboring buildings. *Solar Energy* 180, 717–734. https://doi.org/10.1016/j.solener.2019.01.023

Levinson R, Akbari H. 2010. Potential benefits of cool roofs on commercial buildings: conserving energy, saving money, and reducing emission of green-house gases and air pollutants. *Energy Efficiency* 3(1), 53 – 109. https://doi.org/10.1007/s12053-008-9038-2

Moujaes SF, Brickman R. 2003. Thermal performance analysis of highly reflective coating on residences in hot and arid climates. *Journal of Energy Engineering* 129, 56 – 68. https://doi.org/10.1061/(ASCE)0733-9402(2003)129:2(56)

NREL 2017. PVWatts Calculator Model. National Renewable Energy Laboratory (NREL). Retrieved from http://pvwatts.nrel.gov.

Parker D, Huang Y, Konopacki S, Gartland L, Sherwin J, Gu L. 1998. Measured and simulated performance of reflective roofing systems in residential buildings. *ASHRAE Transactions* 104(1), 963 – 975. http://www.fsec.ucf.edu/en/publications/html/FSEC-PF-331-98

Paolini R, Zani A, Poli T, Antretter F, Zinzi M. 2017. Natural aging of cool walls: Impact on solar reflectance, sensitivity to thermal shocks, and building energy needs. *Energy and Buildings* 153, 287 – 296. https://doi.org/10.1016/j.enbuild.2017.08.017

Petrie TW, Atchley JA; Childs PW, Desjarlais AO. 2007. Energy savings for stucco walls coated with cool colors. Proceedings of Thermal Performance of Exterior Envelopes of Whole Buildings X, December 2 – 7, Clearwater, FL. https://www.coolrooftoolkit.org/knowledgebase/energy-savings-for-stucco-walls-coated-with-cool-colors

PNNL. 2016a. Residential Prototype Building Models. Pacific Northwest National Laboratory, Richland, WA. Retrieved 2015-10 from https://www.energycodes.gov/development/residential/iecc_models

PNNL. 2016b. Commercial Prototype Building Models. Pacific Northwest National Laboratory, Richland, WA. Retrieved 2015-10 from https://www.energycodes.gov/development/commercial/prototype_models

Revel GM, Martarelli M, Emiliani M, Celotti L, Nadalini R, De Ferrari A, Hermanns S, Beckers E. 2014. Cool products for building envelope—Part II: Experimental and numerical evaluation of thermal performances. *Solar Energy* 105, 780 – 791. https://doi.org/10.1016/j.solener.2014.02.035

Rosado PJ. 2016. *Evaluating Cool Impervious Surfaces: Application to an Energy-Efficient Residential Roof and to City Pavements* (Doctoral dissertation). University of California, Mechanical Engineering Department. Retrieved from http://escholarship.org/uc/item/6bf80485

SBT 2017. What is the difference between CO2 and CO2e?. Sustainable Business Toolkit. Retrieved from https://www.sustainablebusinesstoolkit.com/difference-between-co2-and-co2e/

Schroeder DV. 2011. Understanding the seasons: the sun and the seasons. College of Science, Weber State University. Retrieved from http://physics.weber.edu/schroeder/ua/sunandseasons.html

GTI. 2017. Carbon Management Information Center Source Energy and Emissions Analysis Tool (SEEAT), Version 7.3, Gas Technology Institute. Copyright 2017. Retrieved 2017-05 from http://www.cmictools.com/cmicec/default.aspx

Sleiman M, Ban-Weiss G, Gilbert HE, Francois D, Berdahl P, Kirchstetter TW, Destaillats H, Levinson R. 2011. Soiling of building envelope surfaces and its effect on solar reflectance—Part I: Analysis of roofing product databases. *Solar Energy Materials & Solar Cells* 95, 3385-3399. https://doi.org/10.1016/j.solmat.2011.08.002

Synnefa A, Santamouris M, Akbari H. 2007. Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. *Energy and Buildings* 39, 1167 – 1174. https://doi.org/10.1016/j.enbuild.2007.01.004

Zinzi M. 2016a. Characterization and assessment of near infrared reflective paintings for building façade applications. *Energy and Buildings* 114, 206 – 213. https://doi.org/10.1016/j.enbuild.2015.05.048

Zinzi M. 2016b. Exploring the potentialities of cool facades to improve the thermal response of Mediterranean residential buildings. *Solar Energy* 135, 386 – 397. https://doi.org/10.1016/j.solener.2016.06.021

Wikipedia. 2017. Thermal bridge. Retrieved 2017-06 from https://en.wikipedia.org/wiki/Thermal_bridge

Wilcox S, Marion W. 2008. User's Manual for TMY3 Data Sets, NREL/TP-581-43156. April 2008. Golden, Colorado: National Renewable Energy Laboratory. https://doi.org/10.2172/928611